DETERMINATON OF RELATIONSHIP BETWEEN
WELD QUALITY AND MECHANICAL STRENGTH IN DIFFERENT STEELS

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ABSTRACT

DETERMINATION OF RELATIONSHIP BETWEEN
WELD QUALITY AND MECHANICAL STRENGTH
IN DIFFERENT STEELS

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This study has been conducted to establish a relation between welding quality and strength in various types of steel. This because specification of quality levels higher or lower than required leads to an increase in manufacturing cost.

A procedure has been developed to achieve the above objective. In this procedure EN 25817, EN 288-1 and similar welding and nondestructive testing standards have been taken as a basis. Furthermore, effort has been exerted to ensure that welding is performed in a manner that reflects the actual conditions encountered in the industry to the extent possible. The same principles have been pursued in material selection, and the materials have been selected from the low-carbon manufacturing steel types (St37, St44 and St52) that are frequently used in steel construction, boiler manufacturing and similar manufacturing areas.

The welded pieces manufactured in accordance with the established procedure have been tested through radiographic and ultrasonic examination methods to check whether they conformed to the welding quality standards set in the procedure.

Quality levels B and C of the EN 25817 standard have been selected for this study. The sizes of potential defects of quality levels have been defined within this standard. In this study, plates with weld seam that has no defect have been used for Quality level B and plates with weld seam having gas pores in sizes specified in the relevant standard have been used for Quality level C.

After this stage, the pieces have been subjected to mechanical tests and their strength values have been identified. Thereby, the association between welding quality and strength has been established, enabling us to specify which strength values can be achieved in specific welding quality levels.

Keywords: Welding, Weld Quality, Non Destructive Examination, Strength

ÖZ

FARKLI ÇELİKLERDE KAYNAK KALİTESİ İLE MEKANİK MUKAVEMET ARASINDAKİ İLŞKİNİN TESPİTİ

Soylu, Osman Alper
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Bu çalışma farklı çeliklerde kaynak kalitesi ile mukavemet arasındaki bağlantının tespiti için yapılmıştır. İmalat maliyetinin artmasının sebebi kalite seviyelerinin gereğinden yüksek yada düşük belirlenmesidir.

Yukarıda anlatılan amaca ulaşabilmek amacıyla bir prosedür geliştirilmiştir. Bu prosedürde EN 25817, EN 288-1 ve benzeri kaynak ve tahribatsız muayene standartları dikkate alınmış ayrıca kaynakların mümkün olduğunca sanayide karşılaşılan gerçek koşulları yansıtacak şekilde yapılmasına önem verilmiştir. Aynı hususlar malzeme seçiminde de göz önünde bulundurulmuş ve malzemeler çelik konstrüksüyon, kazan imalatı ve benzeri imalatlar da sıklıkla kullanılan düşük karbonlu imalat çeliklerinden (St37, St44 ve St52) seçilmiştir.

Belirlenen prosedüre göre imal edilmiş olan kaynaklı parçalar radyografik ve ultrasonik muayene metotları ile kontrol edilmiş ve prosedürde belirtilen kaynak kalite seviyelerinde olup olmadıkları belirlenmiştir.

Bu çalışma sırasında EN 25817 standardında belirtilen kalite seviyelerinden B ve C kalite seviyeleri seçilmiştir. Bu standart içerisinde kalite seviyeleri için olası hataların

boyutları tanımlanmıştır. Bu çalışma sırasında B kalite seviyesi için hatasız kaynak dikişine sahip plakalar, C kalite seviyesi için ise ilgili standartta belirtilen boyutlara sahip gaz boşluğu olan kaynak dikişine sahip plakalar kullanılmıştır.

Bu aşamadan sonra parçalar mekanik testlere tabii tutulmuş ve mukavemet değerleri tespit edilmiştir. Böylece kaynak kalitelerinin mukavemet ile ilişkisi tespit edilmiş ve hangi kaynak kalite değerinde hangi mukavemet değerlerine ulaşılabileceği tespit edilmiştir.

Anahtar Kelimeler: Kaynak, Kaynak Kalitesi, Tahribatsız Muayene, Mukavemet

To My Parents

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CHAPTER 1

INTRODUCTION

1.1. Aim of the Study

In globalizing world market, the use of standards in all sectors of industry is gaining importance. The basic purpose of these standards is to achieve a certain level of quality and ensure their repeatability. However, in developing countries such as our country, quantitative values like rate and quantity of production are taken into consideration in industry, rather than quality of production. This fact lowers the quality of production and reduces the competitiveness of our products in the world market.

Welding is a very important joining technique, so it is an essential component of metal manufacturing.

Welding quality is controlled based on the EN 25817 "Arc Welded Joints in Steel-Guidance on Quality Levels for Imperfections" standard and is determined in accordance with this standard. This standard is commonly used worldwide and especially in developed countries, and the welding quality is strictly controlled using both destructive and non-destructive examination methods. However, in our country even a small-scale survey will show that production does not conform to this standard, excluding a few major manufacturers. One of the most important reasons of this that the standard cannot be associated with the strength values and therefore the designer cannot request the appropriate welding quality from the manufacturer and hence this is directly reflected onto the manufacturing cost. If appropriate welding quality is not chosen at the design stage, desired level of strength values cannot be achieved, which results in frequent loss of material and increased manufacturing costs.

1.2. Scope of the Study

The most important issue in this thesis is the selection of materials and welding methods to be used from the materials and welding methods commonly used in practical applications. As a result of a survey conducted in the industry, it was concluded that the materials commonly used in our country for steel construction works and machinery manufacturing were St37, St44 and St52 steel types. Therefore, these three materials were selected to be used in this thesis study. Material thickness was selected as 20 mm, taking into consideration both the frequency of use, the non-destructive examination methods to be used and the possibility to find the material in the market. Detailed specifications of these materials are given in the relevant section.

Shielded Metal Arc Welding (SMAW) was selected as the welding method. This is the most commonly used method of welding in the industry as well as it is the method that fits best to the selected materials and the thickness. For thicknesses up to 5 mm for St37, St44 and St52 steels, Gas Shielded Metal Arc Welding method is used. However, this method is not suitable for the thickness of 20 mm, therefore, SMAW method was used for the welding of our test samples.

The welded specimens were manufactured based on the EN 288-3 “Specification and Approval of Welding Procedures for Metallic Materials” standard and in accordance with the dimensions given here. EN 288-3 standard is a standard used for the verification of the welding method, whereby the appropriateness of the procedure written down for the welded pieces is controlled and the procedure is approved. Thereby, the manufacturing of smaller or larger pieces were prevented and welding quality was assured through appropriate heat distribution. Furthermore, this standard was used in determining the examination methods to be used for each welded piece and in specifying the place where tensile and bending samples would be taken from.

As the objective of the thesis study is to establish a relationship between the welding quality and strength, two different welding qualities determined to enable benchmarking. Accordingly, welding quality levels B and C were selected for thesis studies, using EN 25817 standard. The most important reason for choosing welding quality levels B and C from amongst levels A, B, C and D as cited in the standard is to achieve samples that are closest to practical applications, as stated above.

Welded pieces were manufactured, analyzed through ultrasonic and radiographic examination methods, respectively, and then their welding quality levels were measured. The reason for using both non-destructive examination methods is to detect any possible defects and to be sure about the accuracy of welding quality levels.

Tensile and bending tests were applied to the testing samples taken from the parts, whose welding qualities were measured, as cited in EN 288-3. Testing samples were prepared in accordance with EN 895 "Destructive Tests on Welds in Metallic Materials – Transverse Tensile Test" for tensile test and in accordance with EN 910 "Destructive Tests on Welds in Metallic Materials – bend Tests" for bending test. The relationship between welding quality and strength values was established using the data acquired as a result of these tests.

Details of all these stages and the detailed scope of the study are given in the thesis study.

CHAPTER 2

WELDING

2.1 Fundamentals of Process

In welding two components are joined by heating the region at the interface above the melting point of one or other of the components. Welding is distinguished from soldering and brazing, in which a low melting point filler metal is used to make the joint, as well as from diffusion bonding, in which the temperature at the interface is kept below the melting points of all the phases present.

Nowadays welding is an important manufacturing technology, because welding has many important advantages. The strength of welded joints can be given as a good example for these advantages. Welded assemblies are able to carry loads similar to those supported by the individual components from which they are constructed, without requiring the addition of appreciable mass or volume to the overall assembly. It is the high strength to weight ratio (at reasonable processing costs) that compensates for the high processing temperatures and environmental hazards associated with welding. No mechanical bond can compete in its strength to weight ratio with this load carrying efficiency of a welded joint. If disassembly is not a requirement, then welding is very often the joining method of first choice.

The use of welding is still increasing, primarily because it is the most economical and efficient way to join metals.

Pipe joining by welding offers similar economies. The wall thickness of a pipe should be heavy enough to carry the required load. However, if the pipe is joined by screw threads a heavier wall thickness is used to allow for cutting away a portion of the thickness for the threads. The thinner pipe wall thickness is used for the entire welded pipe system. This reduces the amount of metal required and the cost. The inside surface of the welded joint is also smoother. Large diameter pipes are no longer connected together with screw threads and fittings.

Converting castings to welding allows the designer to reduce weight by reducing metal thickness. In a sense, welding is a design concept which allows freedom and flexibility not possible with a cast construction. Heavy plates can be used where strength is required and thin ones can be used where possible. The uniform thickness rule and minimum thickness required for foundry practice are not necessary for welding. Additionally, high strength materials can be used in specific areas while normal strength materials are used where required.

Welding is the best way to protect and conserve materials by protecting their surface with special metal overlays. Corrosion and wear of metal account for losses running into billions of dollars annually. Together they are responsible for an untold loss of lives. Waste from both of these destructive forces can be greatly reduced by welding. Special alloys are weld-deposited on base metals to provide corrosion-resistant surfaces. Also, hard surfacing overlays can be made by welding to provide special alloys with wear-resistant surfaces. Weld surfacing is used to reduce the easily abrasive and corrosive wear of machinery.

Advantages and limitations of welding can be summarized as follows;

Advantages:

- Welding is the lowest-cost joining method.
- It affords lighter weight through better utilization of materials.
- It gains all commercial materials.
- It can be used anywhere.
- It provides design flexibility.

Limitations:

- Much welding depends on human factor.
- It often requires internal inspection.
- It is restricted by some specifications and codes.

In welding different types of weld geometries are used. Weld geometry is an important welding criterion because it affects strength of welding, welding cost and some other welding properties. Because of importance of weld geometry, several types of weld geometries are used i.e., spot welding, butt-joints, T-joints, lap-welding, etc. However, in our thesis project we use butt-welded joints to reach the aim, therefore, only butt-welding (butt-joints) will be mentioned in this section.

Butt-welding is a conventional weld geometry which is commonly used welding technique to join thick plates together. In butt-welding different weld mounts are prepared by brazing according to the thickness of plates. Most commonly used weld geometries are V shaped, Y shaped and X shaped. In our thesis project, the thickness of our plates is 20 mm, therefore we use V shaped geometry according to the related standard EN 29692 “Metal-Arc Welding for Covered Electrode – Joint Preparations for Steel”. The dimensions of V shaped weld seam are given in the Fig. 2.1.

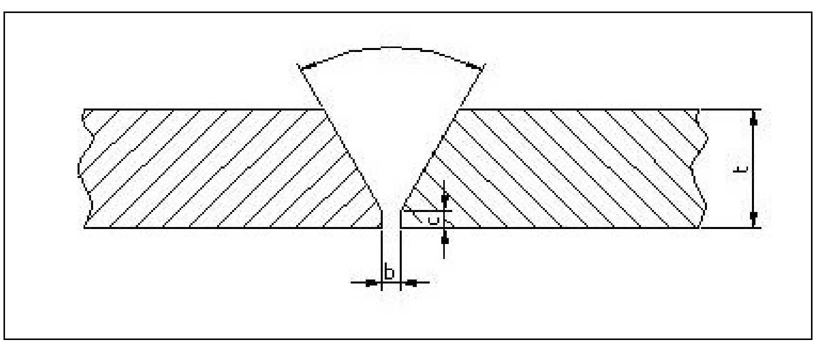


Fig. 2.1: Dimensions of V shaped weld seam

In welding two different stresses play important role on stress distribution. One of them is thermal stresses which occurs with welding and the other one is residual stresses which occurs at heat affected zone (HAZ) after welding. In butt-welding a bar involves more complex stress distribution according to its shape and bending constraint. If the bar is butt-welded then the additional stresses may be result of differential thermal shrinkage on cooling after welding. Therefore all of these stresses affect the strength of welded component and we use tensile and bending tests to measure the strength of component and to determine the relationship between weld quality and material strength.

2.2 Types of Welding

In the 18th century welding process had only one type Electric Arc Welding. In nowadays different types of welding process are used to obtain the most strength full and reliable joining. In this section we classify the welding process according to its type. First of all, general information about types of welding will be given.

Electric Arc Welding is the most common welding method for the assembly of large structures (buildings, ships, bridges, railways, pipelines, electrical power plants, etc…). Arc welding has a long and respectable history dating back to the earliest days of industrialized mass production. The first patent was issued in England in 1885, and this was followed by US patent in 1889. Since then arc welding processes have developed on three separate but related fronts: the properties of the welding electrodes and the metallurgy of the filler metal; flux compositions and the protection of the weld pool from oxidation and composition changes; current and voltage control in the power supply.

Flame Welding, generally based on the combustion of an oxygen-acetylene gas mixture, is probably the second commonest source of heat for the welding of metal components. Before the development of power sources for use in remote locations the oxyacetylene torch was preferred heat source for the on-site welding of steel structures. It is still commonly used for small tasks, where the transport of a power source for arc welding is neither practical nor economic. However, flame welding is less reliable than arc welding for controlling the welding variables (size and temperature of the weld pool and its rate of advance), and, as a result, the structure of the welded joint.

Another important source of heat for fusion welding is the electrical resistance to an imposed current in the contact area between the components, ***Electrical Resistance Welding*** is the most commonly used for automated welding of metal sheet. The technique relies on the limited area of true contact at a loaded mechanical contact. The alloy sheets are compressed between two electrodes which are rolling contact and the sheets are fed between the electrodes at a constant rate. It is always impossible to maintain a constant rate of heat supply, since the area of true contact immediately increases as the temperature exceeds the melting point, lowering the resistance between electrodes, so this is not even attempted. Instead the power source is pulsed, ensuring that power dissipation occurs primarily in the contact area between the sheets which lies immediately beneath the electrodes. As the electrodes advance, subsequent energy pulses repeat the process. The weld line is a "seam" consisting of over lapping spot welds, and the process is referred to as a seam welding.

Electron Beam Welding has developed rapidly with the growth of the aerospace industry. The process is expensive, requiring a massive investment in both vacuum equipment and power generation. The components to be welded are assembled in a large vacuum chamber using a suitable jig. The heat source is a high energy beam of electrons, accelerated from a suitable source and focused on to the work piece by electromagnetic lenses. The work piece is manipulated beneath the focus of the beam by robotic control, which determines both the site of the weld and the rate of advance of weld pool. The welding of complex assemblies achieved under clean (vacuum) conditions, reducing the incidence of welding defects. The only defects commonly encountered with this process are those associated with incomplete fusion or incorrect sitting of the work piece.

Laser Beam Welding has also found some areas of application over the two decades since it was first proposed. Unlike electron beam welding, no vacuum is required.

The focused electromagnetic radiation available from a pulsed power laser provides a localized energy density which may exceed that in an electric arc. However, a large and poorly controlled fraction of the electromagnetic energy is reflected from the work piece, while fumes emitted during welding scattered and absorb the incident beam. Laser welding has developed rather slowly, and has been somewhat overshadowed by both laser-cutting and laser coating technologies, both of which have been proven industrial viability.

As mentioned in the related paragraph, electric arc welding is the most frequently used type of welding. Therefore, the electric arc welding method is used in thesis project. The name of the technique and the detailed information about this technique will be explained in the Section 2.2.1.1.

Electric Arc Welding is divided into two sub groups; Constant Current Electric Arc Welding and Constant Voltage Arc Welding. In the following paragraphs these two different types will be explained.

2.2.1 Constant Current Arc Welding

The power source is the heart of all of the arc welding processes. There are two basic types expressed by their volt-ampere output characteristics. The conventional machine is known as the “Constant-Current” (CC) machine, also known as variable voltage type.

The other type is known as the “Constant-Voltage” (CV) machine. It has relatively flat volt-ampere curve.

The conventional or constant current (CC) type power source may have direct current or alternating current output. It is used for the shielded metal arc welding process, carbon arc welding and gauging, gas tungsten arc welding and plasma arc welding. It is used for stud welding and can be used for the continuous wire process when relatively large electrode wires are used.

Recently arc welding machines have been developed with true constant-current volt-ampere static characteristics, within the arc voltage range. A welder using this type of machine has little or no control over welding current by shortening of lengthening the arc, since the welding current remains the same whether the arc is short or long. This is a great advantage for gas tungsten arc welding since the working arc length of the tungsten arc is limited. In shielded metal arc welding to obtain weld puddle control, it is necessary to be able to change the current level while welding. This done by the machine which can be programmed to change from a high current to a low current on a repetitive basis known as pulsed welding. In pulsed current welding there are two current levels, the high current and the low current, sometimes called back ground current.

2.2.1.1 The Shielded Metal Arc Welding Process (SMAW)

As mentioned in Section 1, aim is to reach the real application procedures as possible as much. Therefore, from the literature and industry survey it is understood that the shielded metal arc welding process is the most frequently used and most suitable welding process for the low carbon steels as St37, St44 and St52 and for the thickness of 20 mm. The detailed information about the shielded metal arc welding is explained in the following paragraphs.

Shielded metal arc welding is an arc welding process wherein coalescence is produced by heating with an electric arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode. The shielded metal arc welding process is shown by Fig. 2.2.

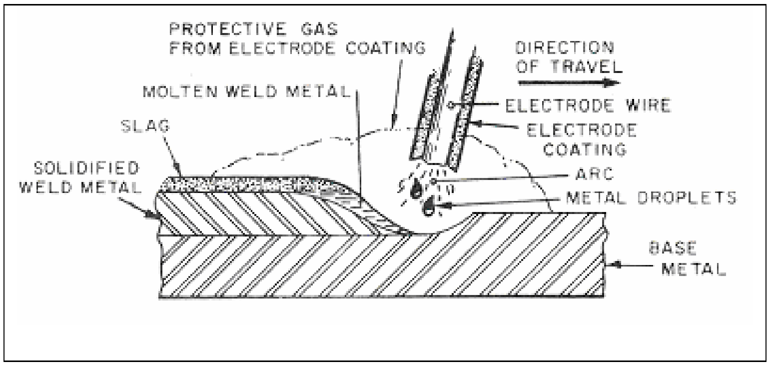


Fig. 2.2: Shielded Metal Arc Welding

The arc is initiated by momentarily touching electrode to the base metal. The heat of the arc melts the surface of the base metal to form a molten pool at the end of the electrode. The melted electrode metal is transferred across the arc into the molten pool and becomes the deposited weld metal. The deposit is covered by a slag, which comes from the electrode coating the arc and the immediate area are enveloped by an atmosphere of protective gas produced by the disintegration of the electrode coating. Most of the electrode core wire is transferred across the arc; however, small particles escape from the weld area as spatter.

The shielded metal arc welding process is one of the most popular welding processes. It has maximum flexibility and can weld many metals in all positions from near minimum to maximum thickness. The investment for equipment is relatively small and most welders have the necessary skill to use the process. It is used in manufacturing operations and widely used in field work for construction, maintenance and repair.

The manual method of applying shielded metal arc welding is most common and represents 99% of all the use of the process. Semiautomatic and machine methods are not used. The automatic method is used and is called gravity welding but has limited applications.

The process has all-position capabilities. Welding in the horizontal, vertical and overhead positions depends on the type and size of the electrode, the welding current and the skill of the welder.

The shielded metal arc process can be used to weld most of the steels and some of the nonferrous metals. Its major use is for joining steels including low-carbon or mild steels, low-alloy steels, high-strength steels, quenched and tempered steels, high-alloy steels, stainless steels, corrosion-resistant steels, and for welding cast iron and malleable irons. It is used for welding nickel and nickel alloys and to a lesser degree for welding copper and some copper alloys. It can be, but rarely is, used for aluminum. It is not used for welding magnesium, the precious metals, or the refractory metals. Shielded metal arc welding is also used for surfacing. As it can be seen from the outlined paragraph this type of welding can be used nearly for every kind of material. For thesis project low carbon steels of St 37, St 42 and St 52 were chosen. This decision was done according to the above mentioned industry survey. While the survey it was seen that the most suitable type of welding for the low-carbon steels is shielded metal arc welding and this technique is the most frequently used one in the industry.

The minimum thickness that can be welded is largely dependent on the skill of the welder. Steel 1.6 mm can be welded by a skilled welder. Thinner material takes extra skill and special precautions. Steel up to 6.4 mm can be welded without the necessity of groove welds if sufficient root opening provided. Thicker material requires joint preparation and multiple passes are required. The largest fillet weld that can normally be made in the horizontal position is 8mm. In the vertical position larger fillets can be made; however, deteriorates if fillets are made over 10mm in a single pass. Maximum thickness is practically unlimited but requires multiple pass technique. In the thesis project the steels with 20 mm thickness were used. This thickness value was chosen according to the industrial survey, non-destructive examination techniques and market conditions. In non-destructive examination the thickness of the material plays an important role in the determination of the weld defects. Especially in radiographic examination the thickness of 20 mm is very suitable for determining the weld defects. Also it was seen that very thin and very thick materials can not be found in the market because of their less consumption and higher price. Therefore, because of all of these practical reasons the material with 20 mm thickness was chosen for the project.

The output characteristics of the power source must be the constant current (CC) type. The normal current range is from 25 A to 500 A using conventional size electrodes. The arc voltage varies from 15 to 35 volts.

The next important piece of the apparatus is the electrode holder, which is held by the welder. The holder firmly grips the electrode and carries the welding current to it.

The covered electrode is the only item of material normally required. The selection of the covered electrode usability and the composition and properties of the deposited weld metal. In order to properly select an electrode it is well to understand the function of the coating, the basis of specifying, the usability factors, and the deposited weld metal properties.

The coating on the electrode provides;

i) gas from the decomposition of certain ingredients of the coating to shield the arc from the atmosphere,
ii) the deoxidizers for scavenging and purifying the deposited weld metal,
iii) slag formers to protect the deposited weld metal with a slag from atmospheric oxidation,
iv) ionizing elements to make the arc more stable and to operate with alternating current,
v) alloying elements to provide special characteristics to the deposited weld metal,
vi) Iron powder to improve productivity of the electrode.

The mechanical properties of the deposited weld metal must equal or exceed those of the base metal. Weld metal must also have approximately the same composition and physical properties.

In our thesis AS B-248 electrode produced by ASKAYNAK-Eczacıbaşı was used. AS B-248 is a basic coated electrode designed for especially in vertical downward position at a very high traveling speed. Weld metal has a high resistance to cracking and because of this property it is especially used for welding operation, where is a high risk of welding stress.
AS B-248 is especially suitable for steel constructions with high static mass. It is recommended for the welding of high carbon steels having high P and S content, for low-alloyed and structural steels of similar strength with the electrode. Also it is suitable for galvanized steels. Because of all these high properties AS B-248 is the most frequently used electrode in the welding process done in industry.

The strength properties of the electrode can be summarized as;

- Tensile Strength [N/mm^2] : 530
- Yield Strength [N/mm^2] : 460
- Elongation (L=5d) [%] : 28
- Impact (ISO-V) : -30°C → 110J
-40°C → 80J

The composition of the electrode is;

- C : 0.07
- Si : 0.5
- Mn : 0.9

When the specifications of the materials used in the thesis project are checked, it is seen that the strength properties and composition of the electrodes are nearly the same.

There is a definite relationship between the welding current, the size of the welding electrodes, and the welding position. These must be selected so that the welder has the molten weld metal puddle under complete control at all times. If the puddle becomes too large, it becomes unmanageable and molten metal may run out of the puddle, particularly in out-of-position welding.

The welder should maintain the steady frying and crackling sound that comes with correct procedures. The shape of the molten pool and the movement of the metal at the rear of the pool serve as a guide in checking the weld quality. The ripples produced on the bead should be uniform and the bead should be smooth with no overlap or undercut. The following five factors are essential for maintaining high quality shielded metal arc welding.

i) It is important to select the proper electrode for each job.

ii) Electrode size choice involves consideration of the type of electrode, welding position, joint preparation, weld size, welding current, the thickness or mass of the base metal, and the skill of the welder.

iii) If the current is too high, the electrode melts too fast and the molten pool is large and irregular and hard to control. If the current is too low there is not enough heat to melt the base metal and the molten pool will be too small and will pile up and be irregular.

iv) If the arc is too long, the metal melts off the electrode in large globules which wobble from side to side giving a wide, spattered, and irregular bead with poor fusion to the base metal. It may also result in porosity, especially with low hydrogen electrodes. If the arc is too short, there is not sufficient heat in the arc at the start to melt the base metal sufficiently and the electrode often sticks to the work.

v) When the speed is too fast the weld pool freezes too quickly. Impurities and gases are not allowed to be released. The bead is narrow and the ripples pointed. When the speed is too slow the metal piles up, the bead is too high and wide with a rather straight ripple.

The factors: correct current, correct arc length and correct travel speed all relate to heat input. An experienced welder inherently adjusts these factors for the optimum weld under every possible condition.

One of the major limitations to the shielded metal arc process is the “built-in break”. Whenever an electrode is consumed to within 50 mm of its original length, the welder must stop. Welding cannot continue since the bare portion of the electrode in the electrode holder should not be used. The welder must stop, chip slag, remove the electrode stub, and place a new electrode in the holder. This occurs many times during the work day and is controlled by the size and length of the electrode. This prohibits the welder from attaining an operator factor or duty cycle much greater than 25%.

Another limitation is the filler metal utilization. The electrode stub loss and the coating loss allows for a total utilization of covered electrode of approximately 65%.

The main technique of the SMAW is given with the above paragraphs. Because of the suitability to the material type and thickness and its good technical properties, Shielded Metal Arc Welding was chosen as the method welding in our thesis project.

2.2.1.2 The Gas Tungsten Arc Welding Process (GTAW)

Gas tungsten arc welding is an arc welding process which produces coalescence of metals by heating them with an arc between a tungsten electrode and the work. Shielding is obtained from a gas mixture. Both pressure and filler metal may or may not be used. This process is sometimes called TIG welding which indicates Tungsten Inert Gas welding. In Europe it is called WIG welding, using Wolfram the German word for tungsten. The gas tungsten arc welding process is shown by Figure 2.3.

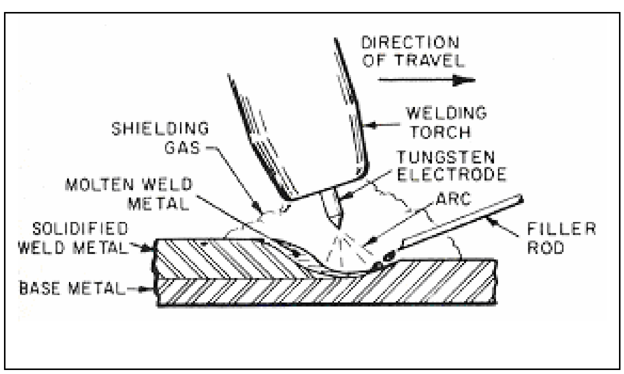


Fig. 2.3: Gas Tungsten Arc Welding

The outstanding features of the gas tungsten arc welding process are:

- It will make high quality welds in almost all metals and alloys.
- Very little, if any, postweld cleaning is required.
- The arc and weld pool are clearly visible to the welder.
- There is no filler metal carried across the arc and so there is little or no spatter.
- Welding can be performed in all positions.
- There is no slag produced that might be trapped in the weld.

This process allows the welder extreme control for precision work. Heat can be controlled very closely and the arc can be accurately directed. GTAW is used in many welding manufacturing operations, primarily on thinner materials and where metal finishing is not desired. It is very useful for maintenance and repair work and for welding die castings and unusual metals. Gas tungsten arc welding is widely used for joining thin wall tubing and for making root passes in pipe joints. The gas tungsten arc welds are usually of extremely high quality.

The major limitation of gas tungsten arc welding is its low productivity. A comparison of the deposition rate of gas tungsten arc welding with gas metal arc welding makes this obvious. Another possible limitation of the process is its higher initial cost. The welding power source is more expensive than the electrode holder. The justification for this is the ability of the process to weld so many metals in thicknesses and positions not possible by shielded metal arc welding.

2.2.1.3 The Plasma Arc Welding (PAW)

Plasma arc welding is a process in which coalescence is produced by heating with a constricted arc between an electrode and the work piece or the electrode and the constricting nozzle. Shielding is obtained from the hot ionized gas issuing from the orifice which may be supplemented by an auxiliary source of shielding gas. Shielding gas may be an inert gas or a mixture of gases, pressure may or may not be used, and filler metal may or may not be supplied. It is shown by Figure 2.4.

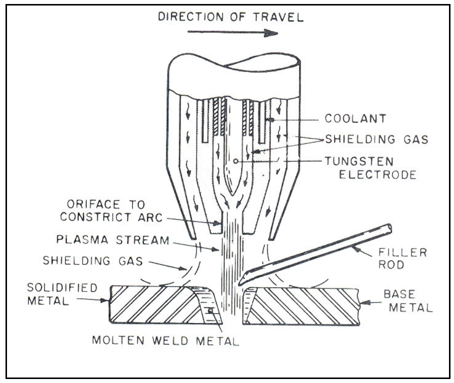


Fig. 2.4: Plasma Arc Welding

Advantages of plasma arc welding when compared to gas tungsten arc welding system from the fact that it has a higher energy concentration. Its higher temperature, its constricted cross-sectional area, and the velocity of the plasma jet create a higher heat content. The other advantage is based on the stiff columnar type arc or form of the plasma which does not flare like gas tungsten arc.

Some of the major uses of plasma arc are its application for the manufacture of tubing. Higher production rates based on faster travel speeds result from plasma over gas tungsten arc welding. Tubing made of stainless steel, titanium and other metals is being produced with the plasma process at higher production rates than previously with gas tungsten arc welding.

2.2.1.4 Carbon Arc Welding Process (CAW)

Carbon arc welding is a process in which coalescence is produced by heating with an arc between a carbon electrode and the work, and in which no shielding is used. Both pressure and filler metal may or may not be used. It can be seen in Figure 2.5.

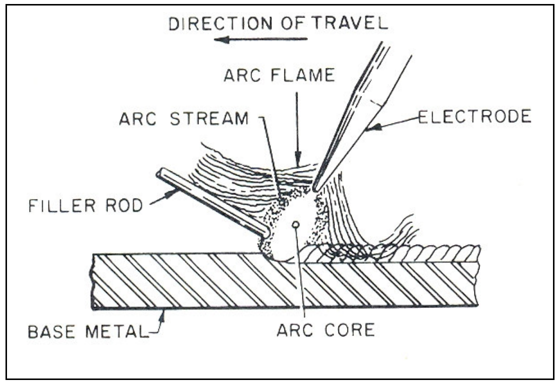


Fig. 2.5: Carbon Arc Welding

The single electrode carbon arc welding process is no longer widely used. It is used for welding copper since it can be used at high currents to develop the high heat usually required. It is also used for making bronze repairs on cast iron parts. When welding thinner materials the process is used for making autogenously weld or welds without adding filler metal. Carbon arc welding is also used for joining galvanized steel. In this case the bronze filler rod is added by placing it between the arc and the base metal.

2.2.1.5 The Stud Arc Welding Process (SW)

Stud arc welding is a process in which coalescence is produced by heating with an arc drawn between a metal stud or similar part and the other work part until the surfaces to be joined are properly heated when they are brought together under pressure.

The stud arc welding process is a unique and is a special application process. It offers tremendous cost savings when compared to drilling and tapping for studs, or to manually welded studs to base metal. Stud welding does not destroy the water tightness or weaken the base metal in the way that drilled and taped holes do.

2.2.2 Constant Voltage Arc Welding

The constant voltage welding machine and the CV system of automatic arc length control is relatively new. The CV principle of operation was introduced at about the same time as gas metal arc welding. It was the combination of these two inventions that has made gas metal arc welding extremely popular. Prior to the introduction of constant voltage welding machine, the drooping characteristic type power source was employed with the voltage-sensing electrode wire feed systems. The reaction time of these systems was not sufficiently fast to avoid burn back and stubbing when using fine wire gas metal arc apparatus.

Welders have long known that when they use a higher current the electrode is melted off more rapidly. With low current the electrode melts off slower. This relationship between melt of rate and welding current applies to all of the arc welding processes that use a continuously fed electrode. This is a physical relationship that depends upon the size of the electrode, the metal composition, the atmosphere that is surrounding the arc, and welding current.

The constant voltage power source has characteristics similar to a standard commercial electric power generator. If the load in the circuit changes, the power source automatically adjusts its current output to satisfy this requirement and maintains essentially the same voltage across the output terminals. This system assured a self regulating arc based on a fixed rate of wire feed and a constant voltage power source. The simplified controls did not require complex circuitry and reversal of the wire feed drive motor.

The constant voltage power source is continually changing current output in order to maintain the voltage drop in the external portion of the welding circuit. Changes in wire feed speed which might occur when the welder moves the gun toward or away from the work are compensated for by momentarily changing the current and the melt-off rate until equilibrium is re-established. The same corrective action occurs if the wire feeder has a temporary reduction in speed. The CV power source and fixed wire feed speed system is self-regulating. It is an excellent wire feed system, especially for semi automatic welding, since movement of the cable assembly often changes the drag or feed rate of electrode wire. The CV welding power source provides the proper current so that the melt-off rate is equal to the wire feed rate. The arc length is controlled by setting the voltage on the power source. The welding current is controlled by adjusting the wire feed speed. In the light of this short explanation about the basic principle of CV system, the sub-groups of the CV arc welding technique can be classified as follows.

2.2.2.1 Submerged Arc Welding (SAW)

Submerged arc welding is a process in which coalescence is produced by heating with an arc or arcs between a base metal electrode or electrodes and the work. The arc is shielded by a blanket of granular fuisable material on the work. Pressure is not used and filler metal is obtained from the electrode and sometimes from a supplementary welding rod.

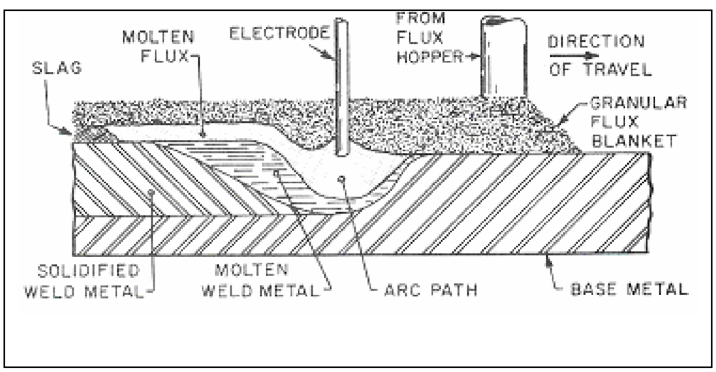


Fig. 2.6: Submerged Arc Welding

The submerged arc welding process, introduced in the early 1930s, is one of the older automatic processes and was originally used to make the longitudinal seam in large pipe. It was developed to provide high-quality deposited weld metal by shielding the arc and the molten metal from the contaminating effects of the air. The major advantages of the process are:

- High quality of the weld metal.
- Extremely high deposition rate and speed.
- Smooth, uniform finish with no spatter.
- Little or no smoke.
- No arc flash, thus minimal need for protective clothing.
- High utilization of electrode wire.
- Easily automated for high-operator factor.
- Manipulated skills normally not involved.

The submerged arc process is widely used in heavy steel plate fabrication work. This includes the welding of structural shapes, the longitudinal seam of larger diameter pipe, the manufacture of machine components for all types of heavy industry, the manufacture of vessels and tanks for pressure and storage use. It is widely used in the shipbuilding industry for splicing and fabricating subassemblies, and by many other industries where steels are used in medium to heavy thicknesses. It is also used for surfacing and build up work, maintenance and repair.

A major limitation of submerged arc welding is its limitation of welding positions. The other limitation is that it is only used to weld primarily mild and low-alloy high-strength steels.

The high-heat input, slow-cooling cycle can be a problem when welding quenched and tempered steels. The heat input limitation of the steel is question must be strictly adhered to when using submerged arc welding. This may require the making of multipass welds where a single pass would be acceptable in mild steel. In some cases, the economics may be reduced to the point where flux-cored arc welding or some other processes should be considered.

In semiautomatic submerged arc welding, the inability to see the arc and puddle can be disadvantage in reaching the root of a groove weld and properly filling or sizing.

2.2.2.2. Flux-Cored Arc Welding (FCAW)

The flux-cored arc welding process in which coalescence is produced by heating with an arc between a continuous filler metal electrode and the work. Shielding is obtained from a flux contained within the electrode. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture. The process is shown in Fig. 2.7.

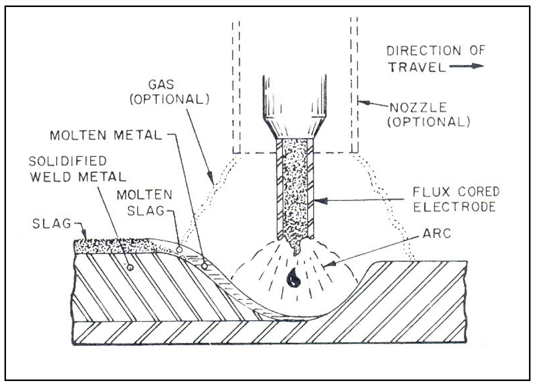


Fig. 2.7: Flux-Cored Arc Welding

The flux-cored arc welding process introduced in early 1950 is an out growth of the gas metal arc welding process. Flux-cored arc welding has many advantages over the manual shielded metal arc welding process. It also provides certain advantages over submerged arc welding and the gas metal arc welding processes. Simply stated, the flux-cored arc welding process provides high-quality weld metal at lower cost with less effort on the part of the welder than shielded metal arc welding. It is more forgiving than gas metal arc welding and is more flexible and adaptable than submerged arc welding. These advantages can be listed as follows;

- High-quality weld metal deposit.
- Excellent weld appearance-smooth, uniform welds.
- Excellent contour of horizontal fillet welds.

- Welds a variety of steels over a wide thickness range.
- High operating factor-easily mechanized.
- High deposition rate-high current density.
- Relatively high electrode metal utilization.
- Relatively high travel speeds.
- Economical engineering joint design.
- Visible arc-easy to use.
- Less precleaning required than gas metal arc welding.
- Reduced distortion over shielded metal arc welding.

This process is becoming increasingly popular. It is widely used on medium thickness steel fabricating work where the fine-wire gas metal arc welding process would not apply and where the fit up is such that submerged arc welding would be unsuitable.

The followings are the limitations to this process:

- Flux-cored arc welding is used only to weld ferrous metals, primarily steels.
- The process produced a slag covering which must be removed.
- Flux-cored electrode wire is more expensive on a weight basis than solid electrode wires.
- The equipment is more expensive and complex than required for shielded metal arc welding; however the increased productivity compensates for this.
- The wire feeder and power source must be fairly close to the point of welding. This is being over-come with the new linear wire feeders and repeaters in the cable.

For the gas shielded version, the external shield may be adversely affected by breezes and drafts. This is also true in the self-shielding version but to a lesser degree.

2.2.2.3 Electroslag Welding Process (ESW)

The electroslag welding is a process in which coalescence is produced by molten slag, which melts the filler metal and the surfaces of the work to be welded. The weld pool is shielded by this slag which moves along the full cross section of the joint as welding progresses. The conductive slag is maintained molten by its resistance to electric current passing between the electrode and the work. Consumable guide electroslag welding variation is a method of electroslag welding in which filler metal is supplied by an electrode and its guiding member.

The consumable guide electroslag welding process is one of the most productive welding processes when it can be applied. Some of its advantages are:

- Extremely high metal deposition in one pass.
- Ability to weld thick materials in one pass. There is only one set up and no interpass cleaning since there is only one pass.
- High quality weld deposit. Weld metal stays molten longer allowing gases to escape.
- Minimized joint preparation and fit up requirements. Mill edges and square flame-cut edges are normally employed.
- A mechanized process: once started, continues to completion. There is little operator fatigue since manipulative skill is involved.
- Minimized material handling. The equipment may be removed to the work rather than the work moved to the equipment.
- High filler metal utilization. All welding electrode is melted into the joint. In addition, the amount of flux consumed is small.
- Minimum distortion. There is no angular distortion in the horizontal plane. There is minimum distortion (shrinkage) in vertical plane.
- Minimal time. It is the fastest welding process for large, thick material.
- There is no weld spatter and metal finishing of the weld is minimal.
- There is no arc flash and so the normal welding helmet is not required.

The major limitation of the process is the welding position limitation. It can be used only when the axis of the weld is vertical. A tilt of up to 15° is permitted, but beyond this the process may not function correctly.

The second limitation is that the process can be used only on steels. Electroslag welding of aluminum so far is limited to pure aluminum and can not be used on the aluminum alloys.

There are several other factors including the fact that the process is different from others and does require familiarization and experience before it can be properly applied for maximum productivity.

2.2.2.4 Gas Metal Arc Welding (GMAW)

Gas metal arc welding is a process in which coalescence is produced by heating with an arc between a continuous filler metal electrode and the work. Shielding is obtained entirely from an externally supplied gas or gas mixture.

There are number of variations of the gas metal arc welding process and the process has been given many different trade names which tend to create confusion. For example, variations are called MIG welding, CO_2 welding, fine wire welding, spray arc welding, pulse arc welding, and electrosalg arc welding and short-circuit arc welding.

The major advantageous of gas metal arc welding are:

- High deposition rates when related to shielded metal arc welding.
- High operator factor with respect to shielded metal arc welding.
- High utilization of filler metal.
- Elimination of slag and flux removal.
- Reduction in smoke and fumes.
- May be automated.
- Skill level in the semiautomatic method of application slightly lower than that required for manual shielded metal arc welding.

- Extreme versatility and wide and broad application ability.

The gas metal arc welding process is the fastest-growing welding process in use today. Its growth is based on replacing shielded metal arc welding for welding thin metals, and for replacing gas tungsten arc welding for nonferrous metals. It is replacing submerged arc in automatic applications. It has replaced gas welding and torch brazing in many uses.

Although it has lots of advantageous it is not suitable for thick materials like the steels used in the thesis. When the material thickness is about 20 mm, filling the weld seam with filler material is not so easy because of multipass. According to the material properties, for thicknesses about 20 mm it is not suitable, also because of its high demand for welder technique it was seen that GMAW is not suitable. At the beginning it was tried to use GMAW as welding technique, however it was seen that the required weld quality levels can not be reached because of the limitations mentioned above. The general limitations of GMAW technique is explained in the following paragraphs.

One problem has been inability to reach inaccessible welding areas with the available guns. Gas metal arc welding guns are not as flexible as the covered electrode used for shielded metal arc welding. However, extensions can be placed on welding guns to reach relatively inaccessible areas.

Often there is the objection of higher priced equipment that requires additional maintenance. When comparing gas metal arc welding to manual shielded metal arc welding, it obvious that more equipment is involved. The productivity of GMAW is sufficiently greater to make the extra cost and extra maintenance a minor factor from an overall cost viewpoint.

Another objection to the process has been the problem of wind and drafts affecting the efficiency of the gas shielding envelope around the arc area. This can be a problem when working outdoors or in drafty locations. It can be overcome by establishing wind breaks or shielding the welding area from direct exposure to fans or open doors or the wind. With a little experience welders are able to use their body to shield the arc area from drafts and breezes.

After outlining the most frequently used welding techniques and the one used in the thesis (Section 2.2.1.1 SMAW), the properties of the materials used in welding and used in thesis will be explained under the following title.

2.3 Materials

Welding can be applied on different materials and it causes different effects on these materials. Because of these effects, all of the materials should be examined in detail. In this section the ferrous and nonferrous materials and their relationship with welding will be explained.

In addition to this, there is an important definition called as weldability. Weldability indicated the welding capacity of a material. In this section we restrict ourselves to the practical factors which determine the weldability of a material.

Many metals and engineering alloys can not be successfully welded, but the list of those that can is impressive: low carbon and low alloy steels, stainless steels and high temperature alloys, nickel and copper alloys, aluminum and magnesium alloys, titanium alloys and many others.

2.3.1 Carbon Steels

Low carbon steels are the most frequently welded structural materials, although the welding cheap, non-structural, thermoplastic components probably accounts for a larger total volume of material. Only steels containing less than 0.3 wt% of carbon are considered suitable for welding, because of the increased probability of both embrittlement and compositional changes at higher carbon contents. Compositional changes are nevertheless common in both the filler and the base metal. These occur primarily through the loss of carbon by oxidation to carbon monoxide gas, although a join in carbon content is also possible when a CO_2 welding process is used. The more readily oxidized alloying additives, especially aluminum and titanium are also easily lost to the slag which is formed on the melt. Almost any heat source can and has been used to weld low carbon steels.

A slag is invariably formed at the surface of the weld and, as in steel making, may be either acid or basic. Acid slags are high in silica and have low viscosities. Basic slags have high manganese oxide content and much higher viscosities. The slag serves a useful function by protecting the metal in the weld pool against excessive oxidation.

The mechanical properties of plain carbon steel welded joints are direct concern in a wide range of engineering structures. Four factors should be considered:

- The influence of weld geometry
- The effect of inclusions
- The presence of embrittling contaminants
- The influence of porosity

Fatigue cracks in a welded joint typically initiate from a reentrant notch, such as that formed on the free surface at the edge of the weld pool. (Fig. 2.8)

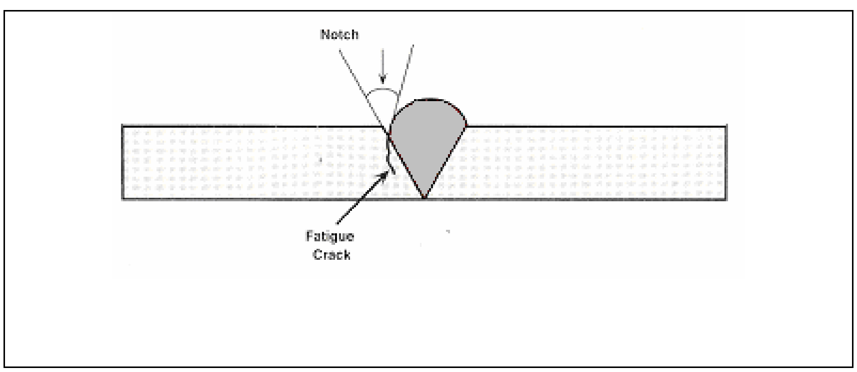


Fig. 2.8: Fatigue Crack

The effect of the notch angle is directly attributable to a stress concentration factor which reduces the fatigue limit. Inclusions also act to reduce the fatigue limit, the reduction in fatigue limit roughly following the dependence on the defect size predicted by fracture mechanics. The embrittling effect of hydrogen contamination on the fatigue life is also indicated. Sulphur is also an embrittling impurity, but the deleterious effects of Sulphur can be mitigated by the presence of manganese, which precipitates ductile manganese sulphide, MnS, in place of the manganese sulphide MnS, in place of the brittle FeS.

Finally, porosity is associated both with the evaluation of gas in the solidifying weld metal and the shrinkage which accompanies the solidification process. The common gasses responsible for porosity are H_2O, CO, H_2 and N_2, all of which dissolve in the melt and are then evolved when the melt solidifies. The distribution, as well as the size and volume fraction of the porosity, determines the extent of any degradation in mechanical properties, and we have already noted the importance of industrial international standards in non destructive evaluation for grading the severity of welding defects.

Compositions and mechanical properties of the materials used in the thesis project are given in Table-2.1 and Table-2.2 respectively.

Table-2.1: Composition of Materials

Material	**C** (max)	**Mn** (max)	**P** (max)	**S** (max)	**Si** (max)	**Al** (min)	**N** (max)	**Cr** (max)
St37	0.17	1.2	0.02	0.02	0.4	0.02	0.012	-
St44	0.18	1.4	0.02	0.02	0.4	0.02	0.012	-
St52	0.2	1.6	0.02	0.02	0.55	0.02	0.012	0.3

Table-2.2: Mechanical Properties of Materials

Material	Yield Strength (MPa)	Tensile Strength (MPa)
St37	225	340
St44	265	410
St52	345	490

2.3.2 Alloy Steels

We define an alloy steel as one that contains at least 80 wt% iron (that is, less than 20 wt% alloying additions). Fusion welding of high strength, high toughness structural steels requires careful control of the welding parameters to avoid brittle failure, which may occur either during the cooling stage of the weld cycle, hot-cracking or subsequently, either before or after the weld is put into service.

Hot cracking is commonly associated with the presence of a low meting point, intergranular liquid phase. An example is boron residues which from a low melting point borate flux. The boundary failure is due to a combination of the presence of a liquid phase at the boundary with thermal shrinkage. Hot-cracking is readily recognized from the wide crack opening of the cracks. The presence of Sulphur is a common cause of hot-cracking in welded low manganese steels. For reasons which are unclear, high nickel alloy steels seem to be more susceptible to hot-cracking than other compositions.

Cold-cracking may be observed in either the HAZ or the weld itself. Four contributing causes have been identified:

- The presence of atomic hydrogen introduced as moisture during welding process.
- The formation of martansite during the weld cycle.
- Unrelaxed residual tensile stresses in the completed weld.
- A welding cycle which results in any other unsatisfactory metallurgical outcome.

Because of the major metallurgical changes that occur in the HAZ, and the very different microstructure of the cast weld metal from that of either the bulk component or the HAZ, filler metal compositions do not approximate the bulk composition. A major consideration is the danger of embrittlement associated with the formation of martensite during the cooling of weld to ambient temperature. One solution to use an austenitic steel for the filler metal, thus side-stepping any problems of martensite formation. A filler metal alloy of composition 18Cr-10Ni-3Mo is one of example.

2.3.3 Stainless and High Alloy Steels

Arc welding and resistance (seam) welding or the welding methods preferred for high alloy, iron base alloys. A major consideration in these materials is the loss of alloying elements during the welding cycle, particularly chromium, which has both a high vapor pressure and a high heat of formation of the oxide. In addition refractory metal alloy additions, such as molybdenum, have volatile oxides which are lost as fume.

Segregation of alloying additions during solidification of the weld metal leads to compositional changes and microstructural inhomogeneity. Carbide precipitation has a major effect on the corrosion susceptibility of high alloy steels and makes some compositions particularly susceptible to stress corrosion cracking, as noted previously. The resistance of austenitic stainless steels to stress corrosion cracking can be improved by niobium additions. This getter residual carbide by forming stable NbC particles and preventing loss of chromium from solution. This is generally a cheaper solution for the steel manufacturer than trying to reduce the carbon content of the steel below the solubility limit for chromium carbide.

The control of alloy steel behavior depends on controlling both carbide stability and the austenite to ferrite transition. Stabilization is done by adding different elements, i.e. Nickel and Cobalt, Chromium and Molybdenum.

Some high performance, specialty steels depend on the precipitation of intermetallic phases to attain their high strength and toughness, and several of these compositions can be successfully heat treated after welding. Heat-treatable, welded steels do not contain carbon, which would be deleterious both the weldability and to the heat treatment response.

2.3.4 Nonferrous Alloys

The classification of engineering alloys into just two groups, ferrous alloys and nonferrous alloys, is justified by the remarkable cost-effectiveness, strength and toughness of the ferrous alloys. The nonferrous alloys melt at temperatures that range from below 600°C (for magnesium and aluminum alloys) to 1200 °C (for copper and nickel alloys) and above (for titanium and special alloys). The heat source requirements are generally less stringent for these lower melting point alloys.

2.3.4.1 Aluminum Alloys

Stoichiometric aluminum oxide forms spontaneously on aluminum as an adherent, stable, non-conducting and protective film. This oxide film must be removed before welding can take place. Friction welding and ultrasonic welding remove the oxide by self-abrasion at the contact surface and solid state bond without exceeding the melting point of the alloy. The application of these processes is limited to simple geometries. In fusion welding, molten halide fluxes are used to dissolve the oxide at temperatures below the melting point of the alloy.

Porosity is a major defect in aluminum alloy welds, and is associated with hydrogen evaluation, originating from hydrated surface films and moisture, together with excessive heat input. Constrained welds, especially in Al-Si alloys which have limited ductility, are susceptible to cracking associated with thermal contraction. The susceptibility depends on the ratio of the thermal stress to the failure strength. As in the case of special steels, some high-performance aluminum alloys can be heat treated after welding to optimize their mechanical properties. These heat treatable welded alloys all require a solution treatment followed by age-hardening in order to develop a uniform precipitate distribution.

2.3.4.2 Magnesium Alloys

Magnesium alloys are no longer regarded as difficult (or dangerous) to weld, although some fire hazard undoubtedly exists. However, magnesium is a very volatile metal, and care must be taken to avoid overheating.

2.3.4.3 Copper Alloys

Porosity is a common defect in welded components of copper alloys, and is usually associated with the evaluation of stream due to the reaction of dissolved hydrogen and oxygen. Copper alloys frequently contain zinc, which is even more volatile than magnesium, so that loss of zinc is to be expected during welding. In general, copper alloys are more frequently brazed than welded, and the lower brazing temperature helps to avoid zinc loss.

2.3.4.4 Nickel Alloys

Welding of nickel alloys requires temperatures approaching 1200°C. Either TIG or MIG processes can be used. Contamination by trace elements is the main source of weld defects. The presence of Sulphur, lead or phosphorus can lead to hot-cracking through the formation of low melting point non-metallics which wet the grain boundaries. Typical sources of contamination are, as in the case of steel, grease or oil which is present on components which have been inadequately cleaned.

Porosity in welded nickel alloys has been traced to the presence of oxide or nitride contamination, leading to the evaluation of CO and N_2 during welding.

2.4 Weld Quality

The demand for more reliable products, and the need to conserve resources make weld quality increasingly important. Quality in the aerospace or nuclear field means 100% reliability of each and every weld. In other fields it means producing welds that are satisfactory to successfully sustain the service encountered. In many fields product liability is a major factor. Quality welding on any product can only be judged with respect to a specific quality standard. This standard must be based on the anticipated service of the product. It must be balanced between the service requirements and the consequence of failure versus economic cost factors. For many products, and in many industrial sectors, weld quality requirements are controlled by rigid codes and specifications.

The need to differentiate between the adequate and the perfect weld has led to research concerning the acceptability of weld imperfection and how these imperfections affect service life. This, in turn, has led to investigations of the degree of imperfection and what may or may not be allowable. Through the years much of these data have been translated into codes and specifications for special types of equipment or weld. The knowledge gained from the field experience and experience of producing weld is reflected in the different codes.

Some of the above mentioned codes, which were also used in the thesis, can be summarized as; EN 25817, EN 29692, EN 288-1, EN 288-2, EN 288-3, etc. In this thesis study, all of these codes were used totally or partially to determine both the welding quality and thesis application procedure.

To produce quality welds it is necessary to look at the total picture, which involves the service requirement of the product, the basic design to produce the product, the design of the welds, the materials selected, and the code or specification to be utilized. This leads to procedures which are normally qualified in accordance with the code. It is then necessary to qualify the welders to see that they adequately comply with the qualified procedure. Finally, it is necessary to determine that the quality level of the welding on the product is in accordance with the specification.

This final factor is the human requirement for continually maintaining quality through inspection techniques and testing. One of the major problems encountered in weld production is the suspicion of the designer that the weld will not be manufactured as expected. Many engineers and designers feel uneasy with weld design for this reason. They feel sure that the weld they have designed will withstand the service requirements.

They also feel that the joint details and procedures are such that the quality required will be attained. The suspicion occurs when they consider workmanship factors that are seemingly beyond their control. They feel, the welder can produce joints equal to the design requirements under ideal conditions, and the welder did produce a quality weld when the performance qualification test was passed; however what assurance do they have that each and every weld in the weld will be of this same quality. The only assurance that can be given to designers is the implementation of a complete quality control program. Such programs save money in the long run as they eliminate the problem of premature field failures, catastrophic disaster, or continual repair work to maintain the product in service.

The implementation of a total quality control program involves a review of the design, of the material involved, very close attention to the weld joints, a review of the qualified procedure, and the adequacy of the procedure to fulfill the needs of service.

For certain classes of work, particularly in the nuclear field, special quality control requirements have been established. These requirements make it necessary to consider all factors and write a quality control program.

A welding procedure is “the detailed methods and practices including all joint welding procedures involved in the production of weld.” The joint welding procedure is the “materials, detailed methods, and practices employed in the welding of a particular joint.” The written welding procedure is a similar “manner of doing” or “the detailed elements of a process or method used to produce a specific result.”

Procedures can also be step-by-step directions for making a specific weld. These procedures are usually written in order to reduce weld distortion or to show how a weld should be made to avoid the possibility of missing welds.

The welding procedure used in the thesis project is given as an annex. Now let's see the defects which are affecting the weld quality item by item.

2.4.1 Weld Defects

The problem of weld defects has become quite complex in the last few years, partially because of the great number of terms and definitions that are being used. For example, a welding flaw is a synonym for discontinuity; discontinuity is preferred term. A discontinuity is "an interception of the typical structure of a weld such as a lack of homogeneity in the mechanical or metallurgical or physical characteristics of the material or weld." A discontinuity is not necessarily a defect. A defect is "a discontinuity or discontinuities which may nature or accumulated effect render a part or product unable to meet minimum applicable accepted standards or specifications." This term designates reject ability. A defective weld then becomes "a weld containing one or more defects." Defect may or may not be cause for rejection or cause for repair. This is normally a matter left to the specifications or codes involved. It is important that we learn to recognize the various different types of weld defects and learn enough about them so that we can recognize them, repair them, and avoid them.

There are various types of weld defects. These defects will be summarized in the following paragraphs. Some of these defects found in the parts and all parts were checked for these kind of defects in the light of EN 25817 "Arc Welded Joints in Steel – Guidance on Quality Levels for Imperfections" for their approval or rejection. As mentioned in Section 1 also, in this study EN 25817 was used for the determination of weld quality, and the welded parts were checked according to the defect dimensions given in this standard.

The permissible dimensions of the weld defects given in the EN 25817 are given below as a table. In Table-2.3, h denotes size of the imperfection and d denotes the dimension of the defect.

Table-2.3: Weld Defects

DEFECT		**Quality Level B**	**Quality Level C**
Cracks		Not permitted	Not permitted
Crater Cracks		Not permitted	Not permitted
Porosity and Gas Pours	Max. dimension of single pore for butt weld	$d \leq 6$ mm	$d \leq 8$ mm
	Max. dimension for a single pore	3 mm	4 mm
Localised Porosity	Max. dimension of single pore for butt weld	$d \leq 6$ mm	$d \leq 8$ mm
	Max. dimension for a localised clustered porosity	2 mm	2 mm
Solid Inclusions	Long Imperfections	Not permitted	Not permitted
	Short Imperfections	2 mm	3 mm
Lack of Fusion		Not permitted	Not permitted
Lack of Penetration		Not permitted	max. 1.5 mm
Undercut		$h \leq 0.5$ mm	$h \leq 1$ mm

2.4.1.1. Cracks

Cracks are the first category of weld defects. A crack is "a fracture-type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement." Cracks are perhaps the most serious of the defects that occur in the welds or weld joints in welds. However, cracks are defects that can be found in other metal products such as forgings, castings and even hot rolled steel products. Cracks are considered dangerous because they create a serious reduction in strength. They can propagate and cause sudden failure. They are the most serious when impact loading and cold-temperature services are involved. Cracks must be repaired.

There are many types of cracks. One way of categorizing them is as surface or subsurface cracks. Surface cracks can be seen on the surface of the weld using the visual testing technique. Surface cracks are shown in figure 2.10.

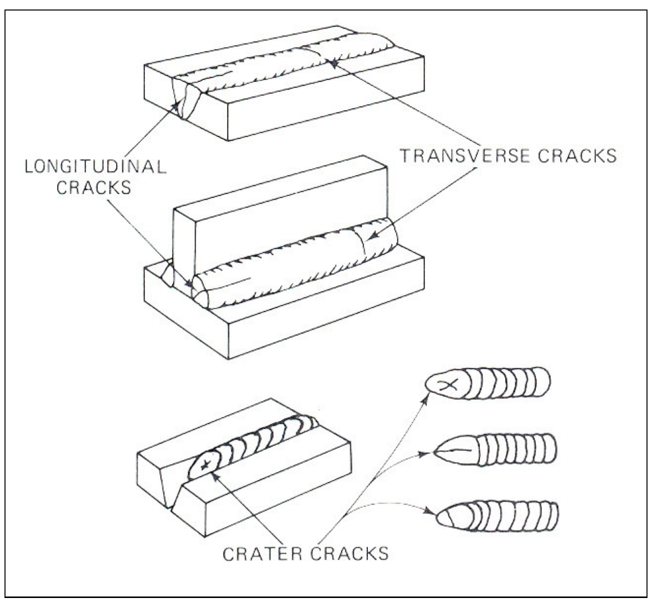


Fig. 2.9: Surface Cracks

The subsurface or internal cracks are also of many types. Some may be in the weld, some in the heat-affected zone- sometimes called under bead cracks, shown by Fig. 2.10.

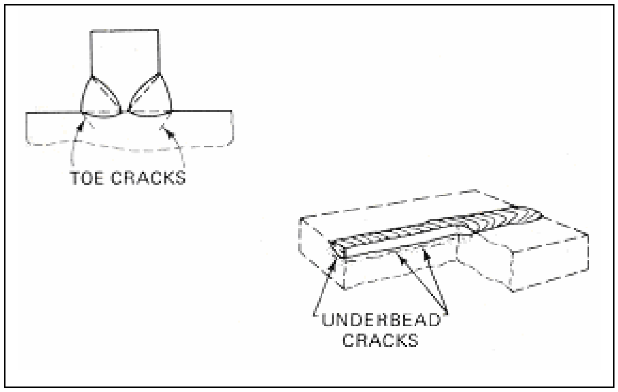


Fig. 2.10: Subsurface Cracks

In general crack in welds or cracks adjacent to welds indicate that the weld metal or the base metal has low ductility and that there is high restraint. Any factor that contributes to ductility of the weld and adjacent metal and high restraint will contribute to cracking. Some of these factors are rapid cooling, high alloy composition, insufficient heat input, poor joint preparation, incorrect electrode type, etc.

2.4.1.2 Cavities

Cavities are the second category of defects. The most common type of cavity is called porosity, defined as "cavity type discontinuities formed by gas entrapment during solidification." Specific defects can be called as gas pockets which are cavities caused by entrapped gas. These are sometimes called blow holes when they are long and continuous. Porosity is not serious as cracks primarily because porosity cavities usually have rounded ends, and will not propagate like cracks.

Cavities, voids and porosity are caused by gases that are present in the arc area, or may be present in base metal, that are trapped in the molten weld during the solidification process. Common causes of porosity are inclusion of gasses from the atmosphere or generated in weld. Other causes for porosity are high Sulphur in the base metal, hydrocarbons on the surface of the metal such as paint, water, oil, moisture from damp electrodes, wet submerged arc flux, or wet shielding gas.

2.4.1.3 Solid Inclusions

Solid inclusions are the next type of defect. Solid inclusions are normally expected to be a subsurface type of defect and would include any foreign material entrapped in the deposited weld metal. The most common type of solid inclusions is a slag inclusion defined as “nonmetallic solid material entrapped in weld metal or between weld metal and base metal.” Another and very similar type of inclusion is a flux inclusion which is entrapped flux from an electrode, from submerged arc flux, or from another source of flux that for one reason or another did not float out of the weld metal as it solidified. Slag inclusions and flux inclusions can be continuous, intermittent, or very randomly spaced. In general flux or slag inclusions are rounded and do not pose sharp concerns like cracks and not quite as serious as cracks.

2.4.1.4 Incomplete Fusion

This is sometimes called lack of fusion or lack of penetration; however the preferred term is incomplete fusion, defined as “fusion which is less than complete.” It is shown by Fig. 2.11.

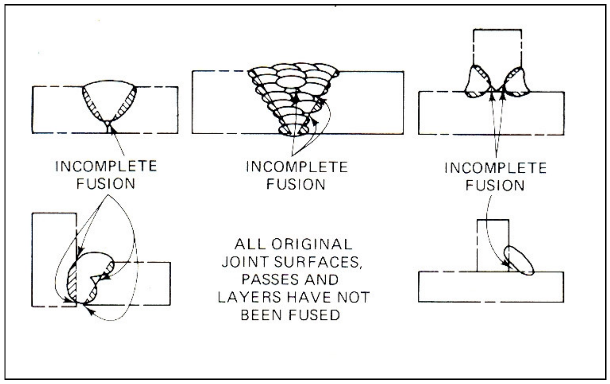


Fig. 2.11: Incomplete Fusion

This can be inadequate joint penetration defined as “joint penetration which is less than specified”. The word penetration is not preferred and the term should be joint penetration or root penetration. Root penetration is defined as “the depth of a groove weld extends into the root of a joint measured on the center line of the root cross-section”. Incomplete fusion as a defect means that the weld deposited did not completely fill the joint preparation or there is a space in between the beads or passes or a space at the root of the joint.

The term penetration means the depth that the groove weld extends into the root of a joint measured on the centerline of the cross section. The defect is the absence of complete fusion of a joint and this provides a stress riser, which is undesirable for welds loaded in fatigue or subject to impacts or low-temperature service. The cause of such defects can be dirty surfaces such as heavy mill scale, heavy rust, grease, the failure to remove slag from previous beads, the fact that the root opening may not be sufficiently large or that the welder technique is not satisfactory. The danger of the defect is the serious reduction in static strength and the production of a stress riser as mentioned above.

2.4.1.5 Imperfect Shape

Imperfect shape or unacceptable contour is the next category. One of the most serious of these defects is undercut, which is shown by Figure 2.12.

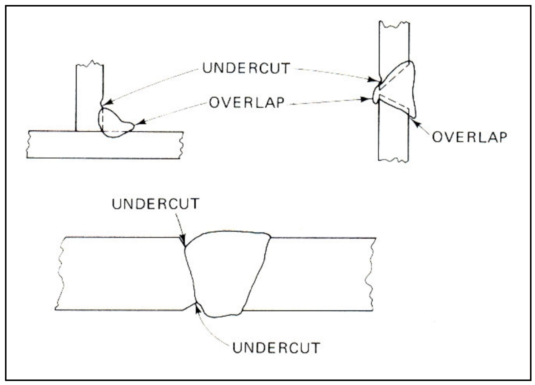


Fig. 2.12: Undercut

Undercut occurs not only on fillet welds but on groove welds as well. Undercut also produces stress risers that create problems under impact, fatigue or low-temperature service. It is normally caused by excessive currents, incorrect manipulation of electrode, incorrect electrode angle or type of electrode. Undercut actually refers more to the base metal adjacent to the weld, whereas imperfect shape is a defect of the weld itself.

There is also problem of excessive reinforcement on the root of the weld, primarily open root groove welds. Excessive reinforcement is an economic waste. It can also be a stress riser and is objectionable from appearance point of view. It is normally a factor involved with fit up, welder technique, welding current, type of electrode, etc. Another similar flow is the concave type contour or lack of fill on the face of the weld or a suck back on the root of a groove weld. The proper term in both cases is underfill, defined “as a depression on the face of a weld or root surface extending below the surface of the adjacent base metal, “as shown by Figure 2.13.

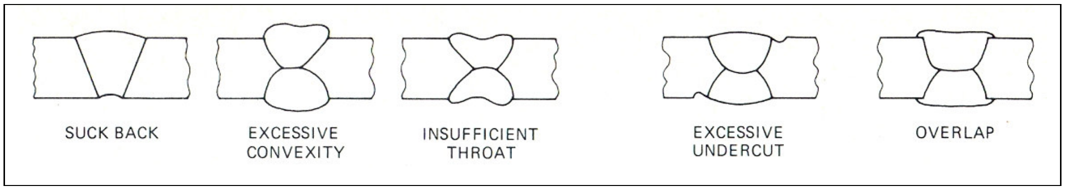


Figure 2.13: Imperfect Shape

Underfill does reduce the cross sectional area of the weld below the designed mounts and therefore is a point of weakness and potentially a stress riser where failure may initiate.

The fundamentals of welding can be summarized as above. All these data was used while the thesis project at different stages, such as the determination of material, determination of welding technique, determination of weld quality, etc. After this generalized information the parts were welded and then they were ready for the non-destructive examination.

CHAPTER 3

RADIOGRAPHIC EXAMINATION

3.1 Definition of Radiography

Ever since the discovery of X-rays in 1885, it has been realized that they can be used for the non-destructive testing of materials as well as people. There are records of "industrial" radiographs being taken as early as 1896.

X-rays are a form of electromagnetic radiation of the same physical nature as visible light, radio waves, etc. but which have a wave length which allows them to penetrate all materials with partial absorption during transmission. Gamma-rays, emitted by radioactive sources are also electromagnetic radiation with exactly the same properties as X-rays and are also widely used in industrial radiography. Neutrons of suitable energy have similar properties of partial absorption in materials and so can be used for radiography; although neutrons are atomic particles and not electromagnetic radiation, "neutron radiography" is a well-established term and technique. Protons have also been used for radiography.

X-rays and gamma rays travel in straight lines outwards from a source: for all practical purposes they cannot be focused, so the usual set-up for producing a radiograph, using a small diameter sources, a sheet of photographic film as detector. By conventional, definitions, a radiograph is "a photographic image produced by a beam of penetrating ionizing radiation after passing through a specimen", and radiography is "the production of radiographs".

X-rays can also be used to produce diffraction patterns to study material structures. These techniques of diffraction and X-ray fluorescence are usually regarded as outside the scope of industrial radiology.
X-ray and gamma-rays are hazardous, and suitable safety precautions must be used when they are employed.

The general principles of Radiography can be summarized as; X-rays travel in straight lines from the source to the film, so that if there is a cavity in the specimen, which causes a lower absorption along the path, more radiation reaches the film, and X-ray image of the cavity is produced which will be projection of the cavity, very nearly natural-size (very slightly enlarged). This is therefore a two-dimensional image of three dimensional cavity.

To produce a radiograph, the X-rays are allowed to reach the film for an appropriate exposure-time, which depends on the intensity of the X-rays, the thickness of the specimen, and the characteristics of the film. The film is then chemically processed (developed, fixed washed and dried), so that the X-ray image can be seen at different levels of film density; the film is then placed on an illuminated screen so that the image can be examined and interpreted.

The majority of specimens to which radiography is applied can be broadly divided into:

i) approximately uniform thickness specimens, such as butt welds, which are examined to detect internal flaws,

ii) non-uniform thickness specimens, such as small castings also examined to detect internal flaws,

iii) assemblies, examined to check correctness of assembly, presence of specific components, spacing between components, etc.

CHAPTER 4

ULTRASONIC EXAMINATION

4.1 Basic Principles of Ultrasonic Examination

Mechanical vibrations can be propagated in solids, liquids and gases. The actual particles of matter vibrate, and if the mechanical movements of the particles have regular motion, the vibrations can be assigned a frequency in cycles per second, measured in hertz (Hz). If this frequency is within the approximate range to 10 to 20,000 Hz, the sound is audible; above about 20,000 Hz, the sound waves are referred to as “ultrasound” or “ultrasonic”.

As an example of a practical application, if a disc of piezoelectric material is attached to a block of steel, either by cement or by a film of oil, and a high voltage electrical pulse is applied to the piezoelectric disc, a pulse of ultrasonic energy is generated in the disc and is propagated into the steel. The velocity of one common form of ultrasonic waves in steel is approximately 6×10^3 m/s, so if the piezoelectric disc is of a suitable thickness to generate waves of frequency 1 MHz, that is a pulse of ultrasonic waves of wave length 6 mm. This pulse of waves travels through the metal with some spreading and some attenuation and will be reflected or scattered at any surface or internal discontinuity such as an internal flaw in the specimen. This reflected or scattered energy can be detected by a suitably placed second piezoelectric disc on the metal surface and will generate a pulse of electrical energy in that disc. Time interval between the transmitted and reflected pulses is a measure of the distance of the discontinuity from the surface and the size of the return pulse can be a measure of the size of the flaw. This is the simple principle of the ultrasonic flaw detector and the ultrasonic thickness gage. The piezoelectric discs are the probes or transducers: sometimes it is convenient to use one transducer as both transmitter and receiver – sometimes called a "transceiver" – by detecting the return pulse between successive input pulses. In a typical ultrasonic flaw detector the transmitted and received pulses are displayed in a scan on a time base on an oscilloscope screen. A simple example can be seen in Fig. 4.1.

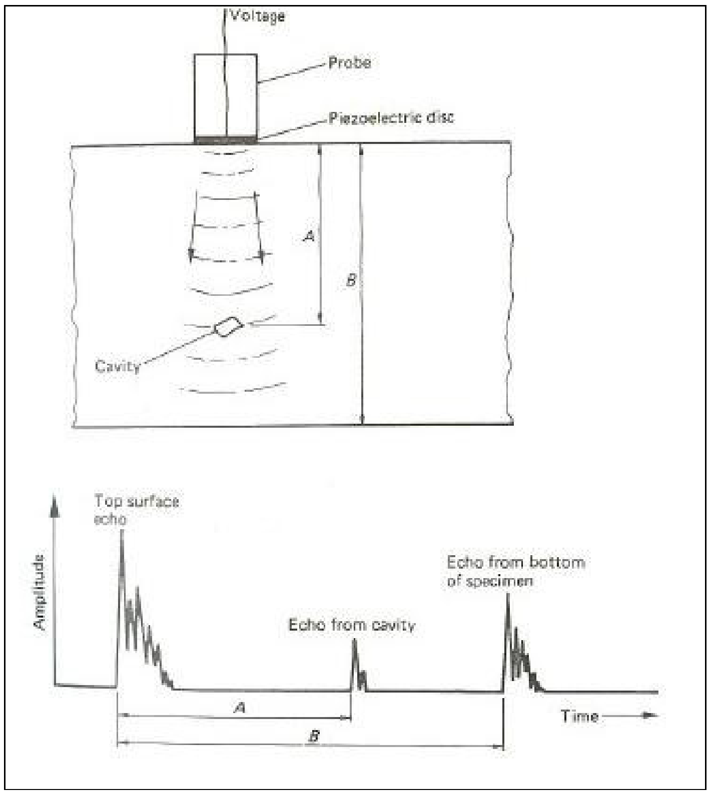


Fig. 4.1: Application of Ultrasonic Flaw Detection

4.1.1 Waves

Ultrasonic waves are mechanical vibrations, not electromagnetic radiation, and so have a different wavelength in different materials. They are possible because of the elastic properties of the material and are due to induced particle vibration in the material. If the particle vibration is sinusoidal, the waves can be assigned a single wavelength, λ, from the well-known formula,

$$f = \frac{c}{\lambda} \quad \text{.........(Eq. 4.1)}$$

c being the wave velocity. A pulse of ultrasonic energy can be considered as the synthesis of a series of purely sinusoidal waves of different frequencies and amplitudes. The narrower the pulse, the grater the number of frequency components.

If the particle motion in a wave is along the line of the direction of travel of the wave, the resulting wave is called a compressional wave or a P-wave. Such waves can be propagated in solids, liquids and gases.

In solid material, it is possible also for the particle movement to be at right angles to the direction of travel of the wave – such waves are called shear waves. These usually have a velocity of approximately half of that of longitudinal waves in the same material and for practical purposes cannot be generated in liquids. They are sometimes called transverse waves.

Various different types of surface wave can also be produced in solid material. Rayleigh waves are only one type of surface wave which can be generated on the free surface of any solid material. They are somewhat analogous to water waves in which the motion of the particles is both transverse and longitudinal in a plane containing the direction of propagation and the normal to the surface. In Rayleigh waves the partial movement is elliptical and such waves exist only in the surface layer of large solids. At greater depths than two wavelengths below the surface the particle motion is practically zero. The surface velocity is usually about 0.9 times the longitudinal wave velocity in most solids. Rayleigh waves on a solid surface are non-dispersive, but in a layered medium dispersive Rayleigh waves are possible.

At an interface either liquid/solid or solid/solid, there can also be an interface wave which is undamped. The particle displacement is in the sagittal plane. This is known as the Stoneley wave. In a thin film (solid/solid) when the particle oscillation is in a plane parallel to the interface, the waves are known as Lowe waves. Lowe waves are dispersive. In plate material where the thickness is of the order of a few wave lengths, various forms of plate wave are possible, the most important forms for NDT being Lamb waves. These are combination of compression and shear waves, the proportion depending on the frequency. In Lamb waves there is therefore a component of particle oscillation at right-angles to the surface and they may be regarded as complex resonance of the plate. Lamb grouped the infinite number of modes in which a plate can vibrate into two main types according to the direction of the particle displacement-symmetrical and asymmetrical.

The wave velocity depends on the thickness, the frequency, the mode order and the material. There is a difference between the phase velocity and the group velocity.

Lamb waves are dispersive. Flexural waves, or guided waves, similar to Lamb waves can be produced in wires (rod waves) or tubes. Rayleigh, Lamb and Lowe waves are used for special applications in ultrasonic testing of materials, but by far the most important types of wave for industrial ultrasonic applications are the compressional and shear waves.

4.1.2 Wave Velocity

The velocities of the various kinds of ultrasonic wave can be calculated from the elastic constants of the material. For compressional waves, in a specimen of large dimensions compared to the wavelength,

$$V_c = \left[\frac{E(1-\rho)}{\nu(1+\rho)(1-2\rho)}\right]^{1/2} \quad \text{.........(4.2)}$$

The shear wave velocity is given by

$$V_s = \left[\frac{E}{2\nu(1+\rho)}\right]^{1/2} \quad \text{.........(4.3)}$$

where E is the Young's Modulus [N/m^2], V_c is the compressional wave velocity, V_s is the shear velocity, ρ is the density of the specimen and ν is Poisson' ratio.

4.1.3 Acoustic Impedance

When an ultrasonic wave is incident on a plane boundary between two media, perpendicular to the surface, some ultrasonic energy is transmitted through the boundary and some is reflected. The percentages of energy transmitted and reflected depend on the specific acoustic impedance, Z, defined for each material as;

$$Z = \rho v \quad \text{.........(4.4)}$$

where ρ is the density of the material and V is the velocity of the wave. For two materials of different acoustic impedances, Z_1 and Z_2, the percentage of energy transmitted, E_T is given by

$$E_T = \frac{4Z_1Z_2}{(Z_1+Z_2)^2} \times 100 \text{.........(4.5)}$$

and the reflected energy E_R, by

$$E_R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 \times 100 \text{.........(4.6)}$$

These formulas are valid for both compressional and transverse waves , but as a transverse wave cannot be sustained in a liquid, a transverse wave is always completely reflected at a solid/solid or solid/gas interface.

A common practical case is the water/steel (or steel/water) interface. Inserting suitable values, it can be calculated that at a water/steel interface 12% of the incident energy is reflected and 68% is transmitted.

A special case of multiple interface is an air-filled crack with a very narrow opening width. Calculated results given by Krautkrämer show that with a gap of about 10^{-6} mm in a steel specimen, the calculated theoretical reflection from the crack is about 70%, and larger gaps reflect effectively 100%. Only therefore with extremely tight cracks is there a possibility of partial transmission across an air gap. In practice, because of the irregularities in the real crack opening widths and the influence of foreign material on the crack surfaces, apparently wider cracks can be semi-transparent to ultrasonic energy nevertheless, unless the crack opening width is less than 1μm, there should be no practical problem in having sufficient reflected ultrasonic for crack detection.

4.1.4 Waves at Oblique Incidence

When an ultrasonic beam is incident at any angle except the normal at an interface between two media having different acoustic impedances, it can produce both reflected and refracted compressional and shear waves.

A simple relationship known as Snell's Law describes the angle of refraction of the transmitted wave;

$$\frac{\sin\alpha}{\sin\beta} = \frac{V_A}{V_B} \quad \text{.........(4.7)}$$

where α and β are the angles of incidence and refraction respectively and V_A and V_B are the wave velocities in two media A and B.

For the reflected wave in medium A, the angle of incidence is equal to the angle of reflection. These expressions hold for both incident compressional and shear waves. When $V_B > V_A$ it is possible to have an angle of incidence α which would make β = 90°. α is then referred to as the critical angle, and for angles of incidence greater than this the wave is totally reflected and no energy is transmitted into the second medium. In case of a water/steel interface, the critical angle for a compressional wave is about 15°. At the interface between two solid media there are two critical angles, one at which the transmitted compressional wave disappears and one beyond which the transmitted shear wave no longer exist.

At an interface it is possible to have mode conversion. This phenomenon describes the conversion of waves while they are transmitted or reflected. This basic principle can be described by using the equations given below.

$$\frac{\sin i}{V_{CA}} = \frac{\sin r_s}{V_{SA}} = \frac{\sin r_c}{V_{CA}} = \frac{\sin R_s}{V_{SB}} = \frac{\sin R_c}{V_{CB}} \quad \text{.........(4.8)}$$

and

$$\frac{\sin i}{V_{SA}} = \frac{\sin r_C}{V_{CA}} = \frac{\sin R_s}{V_{SB}} = \frac{\sin R_C}{V_{CB}} \quad \text{.........(4.9)}$$

where i is the angle of incidence, V_C and V_S are the compressional and shear wave velocities, r is the angle of reflection and R is the angle of transmitted waves.

In practical ultrasonic testing, certain cases are particularly important. The solid/solid case occurs with contact probes on metal surfaces; although usually a thin layer of liquid couplant is used between the solids and this liquid cannot transmit shear waves, so the practical case is solid/liquid/solid. For shear wave inspection which is widely used in weld inspection, the incident angles of interest are those between the two critical angles and the usual requirements is for a transmitted shear wave at 45° - 80°. If a 70° shear wave beam is required in steel, then the angle of incidence in Perspex of the incident compressional wave can easily be calculated by Snell's Law to be 54°.

4.1.5 Diffraction Effects

Along the axis of the beam, the last maximum is located at a distance N from the source where

$$N = \frac{\left(D^2 - \lambda^2\right)}{4\lambda} \;\ldots\ldots\ldots(4.10)$$

which can usually be taken as approximately equal to

$$N = \frac{D^2}{4\lambda} \;\ldots\ldots\ldots(4.11)$$

Distance N is known as the near-field length and the ultrasonic field beyond N is called the far field. The terms "Fresnel region" and "Fraunhöfer region" are sometimes used for the near and far fields respectively.

In typical ultrasonic flaw detection technique, the probe diameter may be 20 mm, and, in steel with 2 MHz frequency, the wavelength will be 3 mm, so the near-field length will be 33.3 mm. In water, with the same probe, near-field length will be 134 mm. If a reflecting flaw is located within the near-field of a probe, obviously the intensity of the reflected energy will depend on whether the flaw is maximum or minimum intensity point in the beam and it will not be possible to make direct use of the intensity of the reflected energy as a measure of the cross-sectional area of the flaw.

Based on a plane, uniformly emitting, ultrasonic source, the profile of an ultrasonic beam is as shown diagrammatically in Fig.4.2. This is very much a theoretical beam shape, as in practice the beam edges are not sharp cut-offs and edge effects have been neglected; furthermore this purposes a continuous wave rather than the ultrasonic pulse which is normally used in ultrasonic flaw detection.

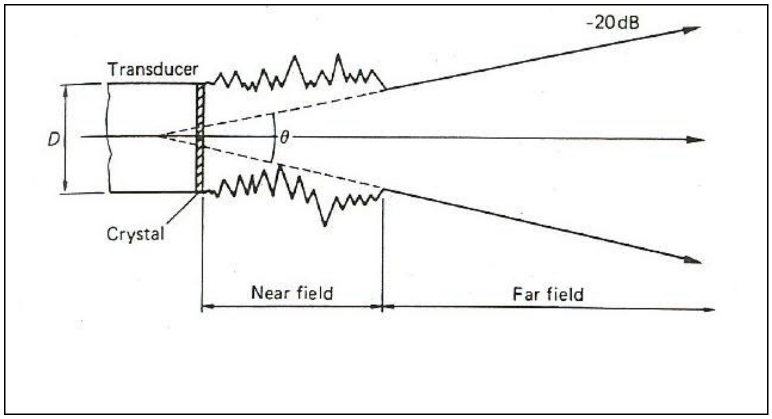


Fig 4.2: Profile of an Ultrasonic Beam

If the beam spread is measured as angle Ø, diffraction theory gives the relation

$$\sin\left(\frac{\theta}{2}\right) = \frac{1.2\lambda}{D} \quad \text{………(4.12)}$$

the beam width to half the centerline intensity by

$$\sin\left(\frac{\theta}{2}\right) = \frac{0.56\lambda}{D} \quad \text{………(4.13)}$$

and the width to one-tenth of the centerline intensity by

$$\sin\left(\frac{\theta}{2}\right) = \frac{1.08\lambda}{D} \quad \text{………(4.14)}$$

4.1.6 Attenuation

In most materials, the ultrasonic intensity is reduced as the ultrasonic beam travels through a material due to various mechanisms, including scattering. The absorption depends markedly on the nature and the structure of the material (grain size and grain orientation) and is also a function of ultrasonic frequency. Many materials are anisotropic so far as absorption is concerned: that is the absorption varies with the beam direction. Formally, ultrasonic attenuation is described in terms of attenuation coefficient, α:

$$I = I_0 \exp(-\alpha t) \text{ ....(4.15)}$$

where I is the intensity at a distance t from an initial intensity I_0. Generally α is taken as the sum of the true attenuation coefficient α_T and the scatter coefficient α_S.

4.2 Application of Ultrasonic Examination on Welds

There is an enormous range of applications of ultrasonic testing, and in this section application of ultrasonic examination on welds will be outlined.

A major application of ultrasonic flaw detection is the inspection and quality control of welds. It is in this field that manual testing is most widely used and where defect-sizing is widely employed, and although many of the procedures to be described are also used in other applications, they will be described here in terms of the testing of butt-welds in ferritic steel, in the thickness range 6-200mm.

Nearly all large industrial countries have produced national standards on ultrasonic weld testing. In Section 7, the standards and their usage will be explained, and using these standards all testing conditions will be chosen.

Most of these examinations are carried out with a hand-held shear wave probe and this must be calibrated, together with the equipment, using the calibration block and test procedures. At a minimum, time base linearity (± 1%), the amplifier linearity (± 1dB) and the calibration gain control (± 1dB) on the equipment should be checked; the probe resolution, index point, frequency, shear wave beam angle, and the beam profile of each probe must also be known. The signal-to-noise characteristics of the probe-plus-equipment should be checked, and for some applications its desirable to know the length of the near-field death zone.

On the weld itself, it is essential to know the weld preparation (the shape of the joint) and to have marked datum line showing the weld centerline. As much as possible information should be obtained on the type of material, heat treatment, welding procedure, and surface condition. A cross-sectional drawing showing the faces, surface counters and the actual thickness is an essential preliminary requirement, particular on complex structures such as nozzles and cross-over pipe work. The metal surface where the ultrasonic probes are to be applied must be free form spatter and reasonably smooth: a surface finish not rougher than 4 µm (Ra) is desirable.

Usually, preliminary ultrasonic examination of the parent metal adjacent to the weld is made, using a compressional wave probe, to detect any laminations or lamellar tearing through which the ultrasonic beam might have to pass doubt, such as in applications where the inside surface is accessible, this must be accurately located either by a compressional wave probe on the weld surface, or if the surface is rough, by a pair of shear wave probes on either side. The precise location of the weld bead and the centerline is vital to success in correct interpretation.

The most important part of a weld, from the point of view significant defects, is the weld root and this is normally examined first. Lack of root penetration, lack of root fusion, and basal cracks can occur in this region, and must be distinguished from an undressed root bead. On single-sided welds, a separate scan should be carried out whenever possible with the probe positioned against a guide bar at the exact half-skip distance to the root.

A 45° to 70° shear wave high resolution probe should be used, the angle depending on the weld thickness and the geometry restrictions. Accurate probe calibration and accurate probe positioning are necessary to separate the echoes from the edge of a root bead and a root crack (Fig. 4.3). The same basic principles apply to double-V welds, for detecting lack of root penetration. The main volume of the weld metal is examined by moving probe between positions A and B shown in Fig. 4.4 as the probe is traversed along the length of the weld seam. Position A covers the lower portion of the weld at half-skip distance and position B the upper portion at full-skip distance. Additional traverses are necessary to detect transverse defects.

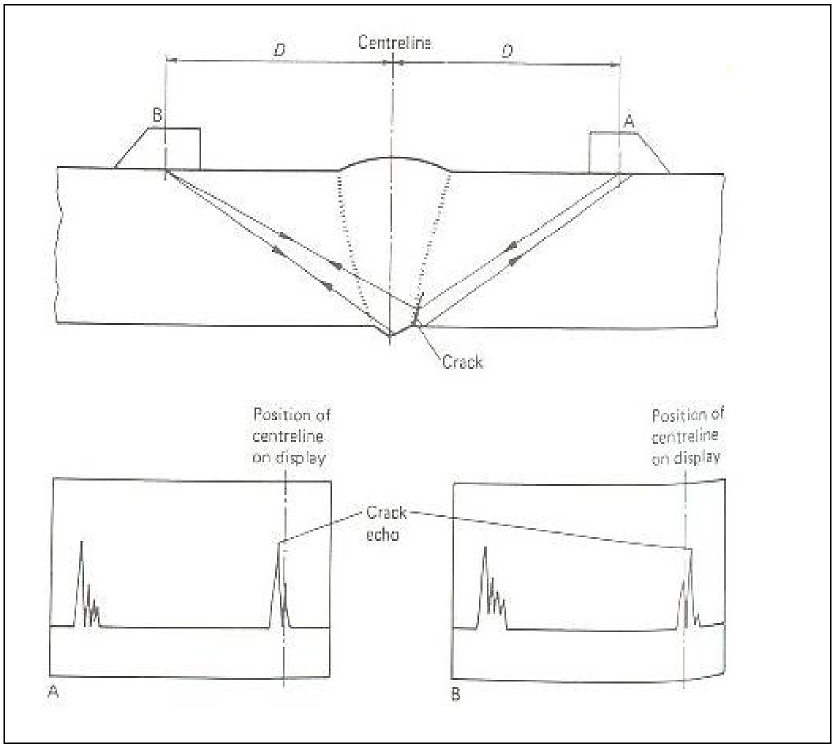


Fig. 4.3: Root Crack

Special slide-rules, which are effectively location diagrams on which an enlarged image of the weld is positioned, are available, to assist converting the ultrasonic measurement into flaw locations. For weld up to 100mm thick, it is recommended that probe scanning is carried out from both sides of the weld on one surface. For thicker welds and critical applications, scanning should be carried out from both sides and both surfaces, whenever possible.

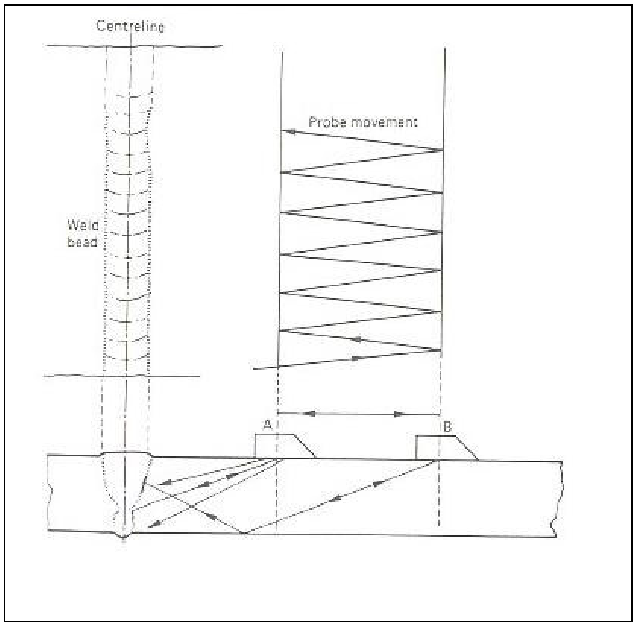


Fig. 4.4: Ultrasonic Scan Path

These are techniques for weld defect location and often the location of a defect automatically identifies the nature of the defect. More information of the nature of the defect can be obtained by observing the changes in the pulse shape as the probe is moved across the defect, or as the probe is rotated slightly. This dynamic image is, to some extend, a function of the height of the defect, but also provides other information. Thus a planar defect such as a smooth crack or a lack of side wall fusion will give a markedly directional indication, disappearing rapidly with change of beam angle, whereas the response from a similar-sized slag inclusion is more persistent, as well as being different in shape.

CHAPTER 5

TENSILE TESTING

5.1 Introduction

The tensile test is the most obvious kind of mechanical test which can be carried out on a material and it is therefore applied more often than most others. Indeed, many of the other forms of mechanical test related to fatigue creep or notch toughness for example, were only developed for each case when it became obvious that simple tensile test results were inadequate to characterize the particular behavior. Tensile tests are multi-purpose in character, in the sense that the results are typically applied in a variety of contexts. For example, the purpose may be to:

- Obtain data relevant to design or the prediction of service performance
- Provide indices which will be used to compare materials for selection purposes
- Provide information for quality control
- Obtain data relevant to the control of forming or fabrication
- Provide a tool for fundamental studies of material behavior

These different applications often become confused and ideally, different procedures and measurements should be employed depending on which function the tensile test is supposed to be fulfilling. For example, for quality control, the main emphasis might be on comparability and convenience, whereas tests related to service performance should be more concerned with accurate simulation of the service environment. For some materials different standard procedures, appropriate to different functions, have in fact been established, but for most materials, only one standard is available to cover all needs.

As a summary; tensile test has always occupied a central role in the design of load-carrying structures and strength technology in general.

5.2 Tensile Test Data

The quantities derived from a tensile test are best considered by reference to the deformation behavior of test piece when subjected to a continuously increasing tension load until it breaks. The behavior of one common structural material is illustrated by the load/elongation curve for mild steel, obtained by plotting the increase in length of a reference length of a test piece of uniform cross-section against the applied load, as shown in Fig. 5.1. Up to the point A, an elastic extension occurs; if, at any stage, the load were removed, no applicable elongation would persist. At "A" sudden elongation occurs without any increase of load; this behavior is known as yielding. The coordinates of the point A thus represent the load elongation at which the test piece stops behaving purely elastically under the tensile load, and the proportionally between stress and strain cases to hold. The plastic permanent strain which takes place when this elastic limit is exceeded arises from the resolved shearing forces setup in the material by the tension load and evidence in support of this can often be observed in tests of mild steel plate test pieces with machined surfaces. Shortly after the initial yield, narrow bands of plastically deformed material can be seen clearly in contrast with the generally undisturbed surface.

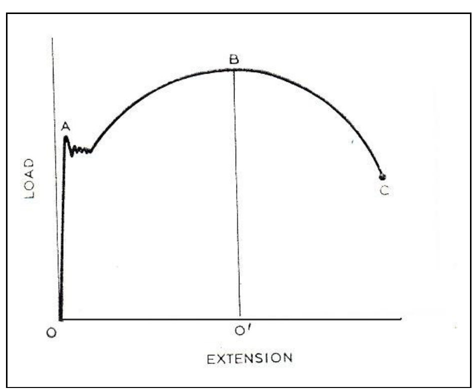


Fig. 5.1: Load-elongation Curve

The load fluctuates erratically without rising above the level of A while yielding takes place; during this stage the elongation is quite large in comparison with that occurring up to the point A. When yielding is complete the load begins to rise again, continues to do so quite slowly until it reaches a maximum value at B, while the elongation increases considerably and quite uniformly along the reference length. After the point B is passed the load falls off steadily while a more localized elongation takes place in one part of the test piece, where it is said to neck. Load continues to fall while necking proceeds, until the local reduction in cross-section is appreciable, and fracture occurs at a load represented by the point C; in the case of a test piece of circular cross-section, the cup and cone type fracture is measured with a ball-ended micrometer, and from it the percentage decrease in cross-sectional area can be computed from the original value.

Almost all the elongation occurring after the yield point A is of a permanent character. This does not, however, mean that the material has lost its elastic property; if on arrival at B, the load is removed, the steel contracts to small extent, retaining a permanent elongation represented by OO’, such that the lines O’B and OA are approximately parallel. On reloading, the relation between load and elongation follows approximately the same path, i.e. O’B.

The slope of the load/elongation curve varies considerably from one metal to another, in which the behavior of different structural materials is compared. Quantitative data which may be required of a tensile test are measures of the elastic behavior up to the point A in Fig. 5.1 or an equivalent point, of the stress required to reach this point, of the breaking strength of the material, and of the extent it stretches before fracturing; the percentage reduction of area at fracture, mentioned above, may also be required.

To render results as far as practicable of test piece size, the principle of similarity is involved, and a range of test pieces is designed according to the related standards such as EN 895 “Destructive Tests on Welds in Metallic Material – Transverse Tensile Test”.

Parameters employed and properties measured in the tensile test are defined in the following manner;

Gauge Length: A length of the parallel portion of the test piece used for the measurement of strain. It is useful to draw a distinction between the original gauge length, L_0, marked on the test piece for the purpose of measuring the percentage elongation after fracture, and other gauge lengths spanned by extensometers for particular measurements, by designated these “extensometer gauge lengths”.

Extension: The increase of any gauge length from its original value at any moment in a test.

Stress: The nominal value of unit stress, i.e. the load divided by the original cross-sectional area of the parallel portion of the test piece.

Strain: Extension divided by the original gauge length.

Young’s Modulus of Elasticity: Increment of stress divided by the corresponding increment of strain for the initial (straight) part of the load/extension (or stress/strain) diagram. For some materials, no clearly defined straight part exists: the line curves from the start. If a modulus is required in such a case, either of two courses may be followed. A “chord” value can be computed corresponding to two points. A modulus computed in this manner is usually known as a secant modulus. Alternatively, the test piece may be unloaded from a higher point on the curve and reloaded. The reloading line will often be straight over much of its length, and parallel to the initial part of the first loading line.

Yield Stress: The stress at which strain first increases without an accompanying increase of stress. This quantity is not specified for non-ferrous metals which, in common with a good many steels, do not exhibit any clearly defined yield point.

Tensile Strength (R_m): The maximum load divided by the original cross-sectional area of the test piece.

Percentage elongation after Fracture, A: The permanent extension of the gauge length, expressed as a percentage of its original value (L_0), i.e.

$$100 \times \frac{L_f - L_0}{L_0}$$

L_f: is the final gauge length after fracture
L_o: is the original gauge length before test

Percentage Reduction of Area (Z): The maximum decrease in cross-sectional area expressed as a percentage of the original cross-sectional area, i.e.

$$100 \times \frac{A_0 - A_f}{A_o}$$

A_f: is the minimum cross-sectional area after fracture
A_o: is the original cross-sectional area

Engineering Stress and Strain: The results of a single test apply to all sizes and shapes of specimens for a given material if the force is converted to stress and the distance between the gauge marks converted to strain. Engineering stress and engineering strain are defined by the following equations.

$$\sigma = \frac{F}{A_o} \quad \text{.........(5.1)}$$

$$\varepsilon = \frac{L - L_o}{L_o} \quad \text{.........(5.2)}$$

where, A_o is the original cross-sectional area of the specimen before the test begins, L_o is the original distance between the gauge marks, and L is the distance between the gauge marks after force F is applied. The stress-strain curve shown in Fig. 5.2 is used to record the results of a tensile test.

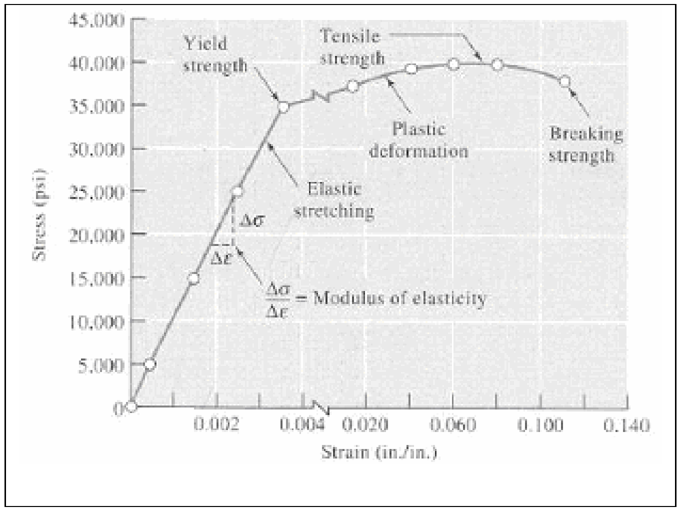


Fig. 5.2: Stress-Strain Curve

All of the tensile properties given above will be outlined in the following paragraphs item by item.

5.2.1 Yield Stress & Strength

The yield strength is the stress at which plastic deformation becomes noticeable. In metals, this is usually the stress required for dislocations to slip. The yield strength therefore is the stress that divides the elastic and plastic behavior of the material. When designing a part that will not plastically deform, we must either select a material that has a high yield strength or make the component large so that the applied force produces a stress that is below the yield strength.

The stress-strain curve for certain low-carbon steels (case for the thesis project) displays a double yield point as shown in Fig. 5.3. The material is expected to plastically deform at stress σ_1. However, small interstitial atoms clustered around the dislocations interfere with slip and raise the yield point to σ_2. Only after we apply the higher stress σ_2 do the dislocations slip. After slip begins at σ_2, the dislocations move away from the clusters of small atoms and continue to move very rapidly at the lower stress σ_1.

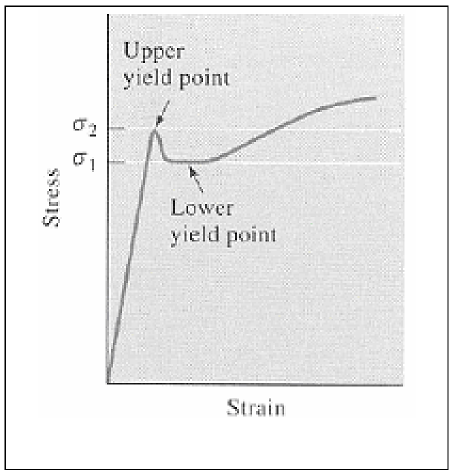


Fig. 5.3: Lower and Upper Yield Point

Low alloy steels or carbon steels exhibit any marked yield, but the great importance of these metals as structural materials has led to the specification of yield stress as one item in quality control, and its use as a design criterion.

Yield, with no other qualification, is in fact a rather indeterminate quantity. With the sudden increase in strain, the load falls off a little and fluctuates erratically while the whole parallel length undergoes the strain. The yield stresses are defined and they can be seen on the Fig. 5.3.

- Upper yield stress: The stress at which yield begins

- Lower yield stress: The lowest stress at which yield proceeds

Customary procedure has in the past been to observe only the first of these. Using a single-lever machine, it is virtually impossible to determine the second accurately. It has long been known, however, that the upper yield stress can be greatly influenced by the degree of axiality of the applied load-remarkably high yields have been reported in tests where care has been taken to ensure that loading is truly axial. The grawing realization that the upper yield stress can be so greatly influenced by the testing techniques employed has led to a tendency to attach greater importance to the lower yield stress.

5.2.2 Tensile Strength

The stress obtained at the highest applied force is the tensile strength, which is the maximum stress on the engineering stress-strain curve. In many ductile materials, deformation does not remain uniform. At some point, one region deforms more than others and a large local decrease in the cross-sectional area occurs. This locally deformed region is called a neck. Because the cross-sectional area becomes smaller at this point, a lower force is required to continue its deformation, and the engineering stress, calculated from the original area A_0 decreases. The tensile strength is the stress at which necking begins in ductile materials.

5.2.3 Modulus of Elasticity

The modulus of elasticity or Young’s modulus, E is the slope of stress-strain curve in the elastic region. The relationship is Hooke’s Law:

$$E = \frac{\sigma}{\varepsilon} \quad \text{.........(5.3)}$$

The modulus is closely related to the binding energies. A steep-slope in the force-distance graph at the equilibrium spacing indicates that high forces are required to separate the atoms and cause the material to stretch elastically. Thus, the material has a high modulus of elasticity. Binding forces, and thus the modulus of elasticity, are typically higher for high melting point materials.

The modulus is a measure of the stiffness of the material. A stiff material, with a high modulus of elasticity maintains its size and shape even under an elastic load.

5.2.4 Ductility

Ductility measures the amount of deformation that a material can withstand without breaking. We can measure the distance between the gauge marks on our specimen before and after the test. % Elongation describes the extent to which the specimen stretches before fracture;

$$\% ELONGATION = \frac{L_f - L_o}{L_o} \times 100 \quad \text{………} \; (5.4)$$

where L_f is the distance between gauge marks after the specimen breaks.

A second approach is to measure the percentage change in cross-sectional area at the point of fracture before and after the test. The percent reduction in area describes the amount of thinning undergone by the specimen during the test.

$$\% \quad REDUCTION \quad IN\ AREA = \frac{A_o - A_f}{A_o} \times 100 \; \text{………} \; (5.5)$$

where A_f is the final cross-sectional area at the fracture surface.

Ductility is important for both designers and manufacturers. The designer of a component prefers a material that displays at least some ductility, so that if the applied stress is too high, the component deforms before it breaks. Fabricators want a ductile material in order to form complicated shapes without breaking the material in the process.

5.3 Tensile Test Specimen

5.3.1 Sampling

Galileo (1564-1642) was the first to propose cross-sectional area as a characterizing parameter for strength calculations and tests. He showed how to relate the failure strengths of small samples and full-scale structures.

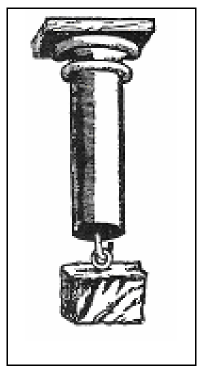


Fig. 5.4: Galileo’s Tensile Test Apparatus

However the need to scale other dimensions of a test piece aside from the cross-sectional area was not clearly established until the late 19th century and it is worth recalling the background to this discovery.

By the middle of the 19th century, more and more iron and steel products were appearing on the market and users of these products turned to tensile testing to settle rival claims about strength and performance. The Glasgow engine makers, Rober Napier and Sons, commissioned David Kirkaldy to set up a testing machine, which would be used to asses the relative merits of two potential replacements for wrought iron, designated “puddle steel” and “homogeneous metal”. His machine may appear crude, even by standards then current, but Kirkaldy applied an enquiring mind and acute observation to produce, according to Timoshenko, the most complete description of the mechanical properties of iron and steel then available. Kirkaldy was the first to suggest that reduction in area that failure could be used to characterize ductility. He also observed various effects of specimen shape and dimensions on strength and ductility and thus drew attention to the need to balance high strength with adequate ductility. He stated clearly for the first time that the failure stress a given material could not simply be assumed to be an invariant property of the material; it depended greatly on test procedures and specimen geometry.

By the end of the 19th century, several meetings to establish uniformity of technique in mechanical testing had been held in European centers and the importance of employing specimens which would be geometrically similar in all respects came to be understood. The application of this principle in relation to ductile failure-elongation is attributed to J. Barba, who stated that the same percentage elongations are obtained in geometrically-scaled cylindrical specimens when the index gauge lengths are corresponding multiples of the specimen diameter. The same conclusion appears to hold approximately true for gauge-length-to-thickness multiplies in the case of rectangular cross-sections of a given width-to-thickness ratio.

Once it had been accepted that a dimensionally similar gauge length should be used, various opinions developed concerning the precise choice of gauge length/diameter multiple. National Standards in different countries in the earlier part of the present century called for gauge lengths varying between 3.5 x diameter and 10 x diameter. The factor which complicates the decision is that the total plastic elongation and a non-uniform or “necked” portion. If a short gauge length is specified, this emphasizes the necking process, whereas a very large gauge length tends to de-emphasize it. As the neck is commonly found to be same where between half a diameter and two diameters long, depending on material, a gauge length some what greater than two diameters should provide reasonable insensitivity to necking variations.

The specimens prepared for the welded parts differ from the basic tensile test specimen mentioned above. As mentioned in the related sections the tensile test is used to obtain basic strength properties of the welded parts. By using the data obtained from tensile test, the strength and quality properties and the relationship between them can easily be understood. A short explanation of historical progress of tensile test specimens is given above and the details of the specimen prepared for the welded parts will be given in the following paragraphs.

5.3.2 Sampling for Welded Parts

The specimens for the welded parts are prepared according to the related standard EN 895. In the above mentioned standard all the details required for the tensile test specimen are explained. The scope of the standard is given as “this standard specifies the sizes of the test specimen and the procedure for carrying out transverse tensile test in order to determine the tensile strength and the location of fracture of a welded butt joint”.

As stated in the scope of standard, the specimen, which is sized and prepared according to the this standard, is for the butt welded part and as mentioned in the Section 7 the welded parts used in the thesis project are butt welded.

First of all to understand the denominations and symbols which will be used in this section, they should be explained and this simple explanation is given below;

- a: Thickness of the test specimen (mm)
- b: width of the calibrated parallel length (mm)
- b_1: width of the shoulder (mm)
- L_c: parallel length (mm)
- L_o: original gauge length (mm)
- L_s: maximum width of the weld after machining (mm)
- L_t: total length of the test specimen (mm)

- r: radius of shoulder (mm)

The test specimen for the transverse tensile test has rectangular cross-sectional area and the shape of the specimen is given in Fig. 5.5.

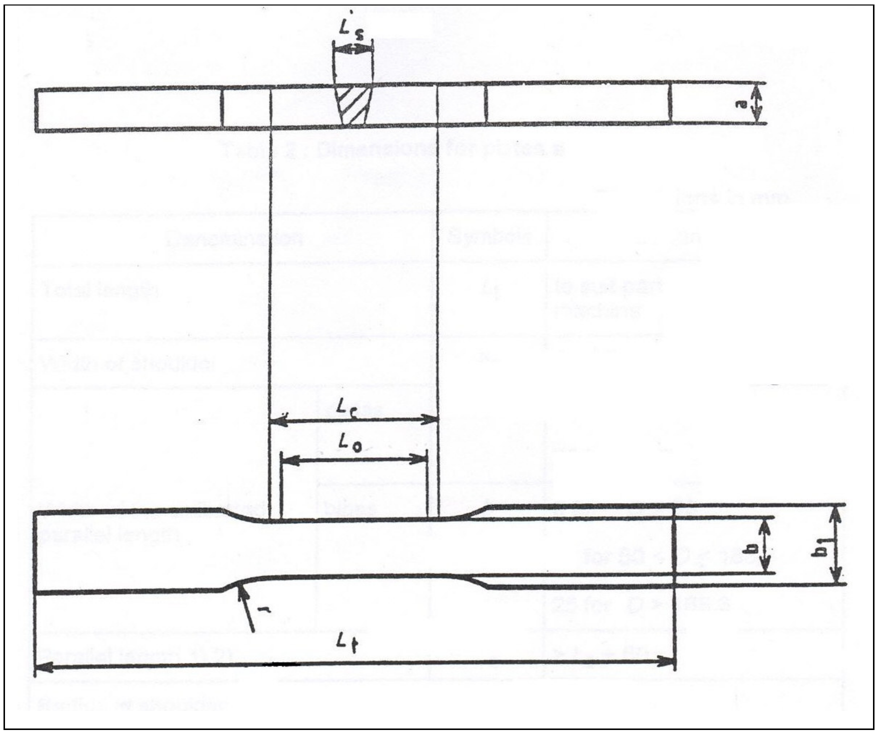


Fig. 5.5: Tensile Test Specimen for Plates

The dimensions given above are determined by the definitions and tables given in the EN 895 and the calculations are given item by item below.

5.3.2.1 Thickness of the Test Specimen (a)

The thickness of the test specimen, a, shall be equal to the thickness of the parent metal near the welded joint. The thickness of the parent metal is 20 mm so the thickness of test specimen will be 20 mm.

$$a = 20 \text{ mm}$$

5.3.2.2 Width of the Calibrated Parallel Length (b)

The width of the calibrated parallel length will be determined from the Table-2 given in the standard EN 895. From this table the width b is determined as 25 mm according to the thickness of the test specimen.

$$b = 25 \text{ mm}$$

5.3.2.3 Width of the Shoulder (b_1)

Width of the shoulder is also determined from Table-2. This dimension is calculated by a simple equation given on the above mentioned table;

$$b_1 = b + 12 \text{ .... } (5.6)$$

if b is width of the calibrated parallel length and it equals to 25 mm then

$$b_1 = 25 + 12 \rightarrow b_1 = 37 \text{ mm}$$

5.3.2.4 Parallel Length (L_c)

It is the length of the dimension between the shoulders of the test specimen and it is calculated by using the equation given below;

$$L_C > L_S + 60 \text{ .... } (5.7)$$

$$L_C = 20 + 60 = 80 \text{ mm} \rightarrow L_c = 80 \text{ mm}$$

5.3.2.5 Radius of Shoulder (r)

This is the machining radius of shoulder, which should be obtained on the test specimen and it is given as;

$$r > 25 \text{ mm}$$

In the Table-2 of the standard EN 895. In our test specimen it is chosen as 30 mm, therefore

$$r = 30 \text{ mm}$$

5.3.2.6 Maximum Width of the Weld After Machining (L_S)

As we mentioned in the Section 7, the weld seam has the V shaped geometry. The angle of the V shape is chosen 60^o from the standard EN 29692 "Metal-Arc Welding with Covered Electrode – Joint Preparations for Steel", therefore by using a simple geometric calculation; the maximum width of weld after machining is taken as 20 mm.

$$L_s = 20 \text{ mm}$$

5.3.2.7 Total Length of the test Specimen (L_t)

According to the standard EN 895, the total length of the length of the test specimen can be chosen according to the testing machine as mentioned in the Table-2 of the related standard EN 895, therefore, the L_t is chosen as 280 mm.

5.3.2.8 Removal of Test Specimens

The test specimen shall be removed transversely from the welded joint in such a way that, after machining the weld axis will remain in the middle of the parallel length of the test specimen.

Shearing is excluded for thickness of more than 8 mm. If thermal cutting or other cutting methods which could affect the cut surfaces are used to cut the test specimen from the welded plate, or from test piece, the cuts shall be made at a distance greater than or equal to 8 mm from the surfaces of the final parallel length of the test specimen. Thermal cutting shall not be used parallel to the original surface of the welded plate or of the test piece. In the thesis project, all specimens were removed from the welded plate by using a sawing machine and to protect the weld seam from heat deposition of cutting the specimens were cut 8 mm wider than their original dimensions.

The final stages of preparation shall be performed by machining or grinding, suitable precautions being taken to avoid superficial strain hardening or excessive heating of the material. The surfaces shall be free from scratches or notches transverse to the test specimen direction in the parallel length, L_c, except for undercut which shall not be removed unless required by the relevant application standard. The surfaces of the test specimen shall be machined in such a way that, all excess weld metal is removed.

After preparation of the test specimen according to the restrictions mentioned above, the tensile test is performed according to the related standard application standard.

CHAPTER 6

BENDING TEST

6.1 Introduction

Such mechanical properties as the average modulus of elasticity between tension and compression, the proportional limit stress, and the modulus of rupture in bending are sometimes found by bending tests.

Bending stresses are computed by the use of equations based on two main assumptions:

- Points in a plane section of the beam before bending remain in a plane after bending. This assumption is known as the "Navier hypothesis". Experiments show that this assumption holds true well beyond the elastic range.
- The material remains elastic with the modulus of elasticity in tension equal to that in compression.

Bend test of ductile materials are usually conducted on a qualitative basis, with no attention paid to the initial stages of bending, but with bending continued far beyond the limit of elastic behavior.

The type of test most frequently used is the simple bend test, in which a round or rectangular section bar is subjected to a considerable plastic deformation in bending. The purpose of the test is normally simply to give some indication of the material's capacity to deform in one particular direction without cracking; to establish a criterion by which performance can be judged it is usual to specify the radius r to which the material is to be bent, and the angle α through which it is to be bent.

The test is frequently applied to finished products such as round or rectangular section bar, and also to test pieces cut from sheet and plate. Tests of different shaped cross-sections are not directly comparable, and it is found, for instance, that for a given radius and angle of bend a test on a round bar of diameter d is less severe test of the material than a test of a bar whose section is a square of sided. Again, increasing the ratio of width to thickness increases the severity of the test. Thus, for strict comparison of the results of tests on material of different thicknesses the other test piece dimensions and the radius of the mandrel should preferably all be in direct proportion to the thickness.

6.1.1 Behavior of Materials Subject to Bending

If forces act on a piece of material in such a way that they tend to induce compressive stresses over one part of a cross-section of the piece and tensile stresses over the remaining part, the piece is said to be in bending. The common illustration of bending action is a beam acted upon by transverse loads; bending can also be caused by moments or couples such, for example as may result from eccentric loads parallel to the longitudinal axis of a piece.

In structures and machines in service, bending may be accompanied by direct stress, transverse shear, or torsional shear. For convenience, however, bending stress may be considered separately, and in tests to determine the behavior of materials in bending, attention is usually confined to beams. In the following discussion, it is assumed that the loads are applied so that they act in a plane of symmetry, so that no twisting occurs, and so that deflections are parallel to the plane of the loads. It is also assumed that no longitudinal forces are induced by the loads or by the supports.

Figure 6.1. illustrates a beam subjected to transverse loading. The bending effect at any section is expressed as the “bending moment” M which is the sum of the moments of all forces acting to the left of the section. The stresses induced by a bending moment may be termed bending stresses. For equilibrium, the resultant of the tensile forces T must always equal to the resultant of compressive forces C. The resultants of bending stresses at any section form a couple that are equal in

magnitude to the bending moment. When no stresses act other than the bending stresses, a condition of "pure bending" is said to exist.

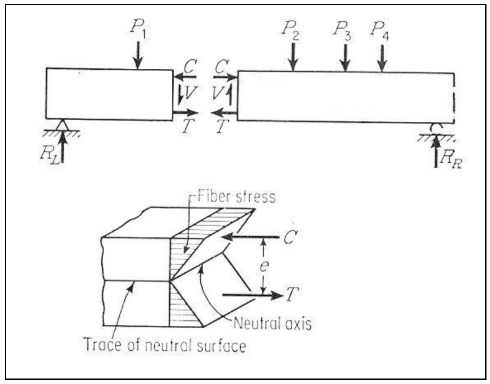


Fig. 6.1: Beam Subjected to Transverse Loading

Pure bending is developed under certain loading conditions; in the usual case, bending is accompanied by transverse shear. The resultant of the shearing stresses across a transverse section equals the total transverse shear V, which is computed as the algebraic sum of all transverse forces to the left of a section. Bending action in beams is often referred to as "flexure".

The variations in total transverse shear and in bearing moment along a beam are commonly represented by shear and moment diagrams, which are illustrated for several cases concentrated loading in Fig. 6.2.

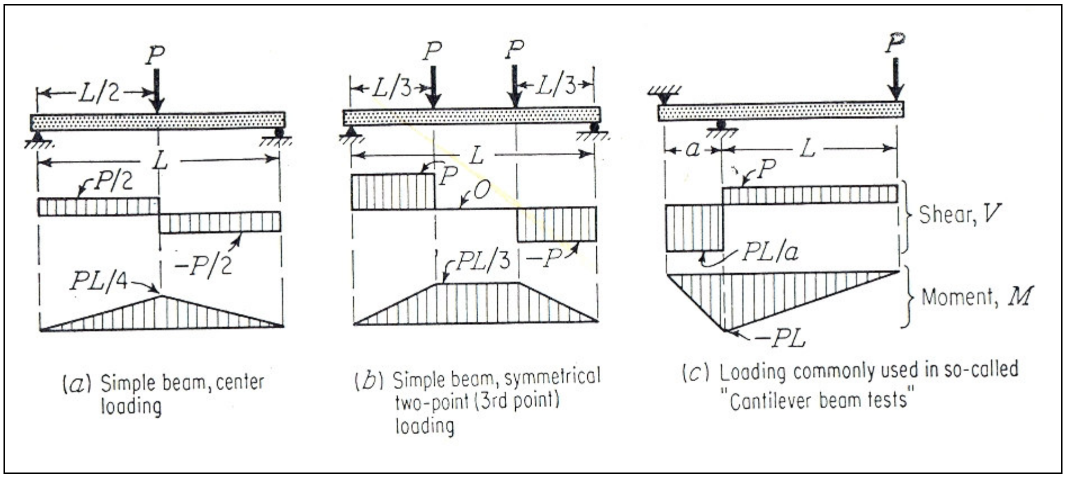


Fig. 6.2: Shear and Moment Diagrams

In the figure given above, Fig. 6.2.a., the loading characteristics of the bending test for the welded parts is given. From this figure it is easily understood that there is definite shear force acting on the weld. The application procedure and the load application details are given in the related standard EN 910 "Destructive Tests on Welds in Metallic Materials – Bend Tests". This application is not usual for bending tests, because in general the residual shear forces are not wanted on the part, generally pure bending is preferred. However, for welded parts, because of welding procedure given in the EN 910 there is a residual shear force. The application of the bending test will be given in the following sections.

In a cross-section of a beam, the line along which the bending stresses are zero is called the neutral axis. The surface containing the neutral axis of consecutive sections is the neutral surface. On the compressive side of the beam the fibers of the beam shorten, and on the tensile side they stretch, thus the beam bends or deflects in a direction normal to the neutral surface, becoming concave on the compressive side.

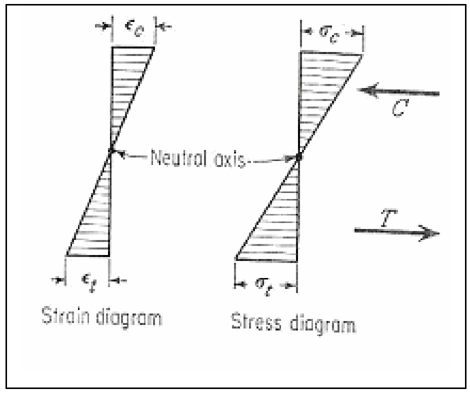


Fig. 6.3: Strain and Stress Diagrams

By summing the moments of the stresses about the neutral axis, the resisting moment within the proportional limit may be found in terms of the extreme fiber stress:

$$M = \frac{\sigma I}{c} \text{ ...... } (6.1)$$

where σ is the stress on extreme fiber, c is the distance from the neutral axis to extreme fiber and I is the moment of inertia of the section about the neutral axis.

In terms of the extreme fiber strains, the moment may be stated as;

$$M = \varepsilon \frac{EI}{c} \text{ ...... } (6.2)$$

where ε is the extreme fiber strain per unit length of beam.

If the beam is of rectangular section, the shearing stress is a maximum at the neutral axis and varies parabolically from a maximum at the neutral axis to zero at the extreme fibers as indicated in Fig. 6.4, the maximum shearing stress is 1.5 (V/A). If shearing stress acts, a plane cross section does not remain plain under load. The deflections due to shear may be computed by summing up the shear strains in the various elements of a beam. In beams in which the ratio of length to depth is about 10 or more, the shearing deflections are sufficiently small compared with bending deflections that they can usually be neglected in practical testing.

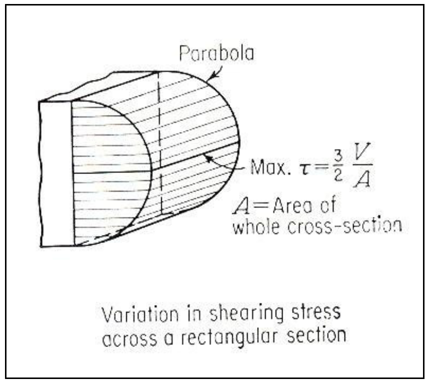


Fig. 6.4: Shearing Stress at Rectangular Section

Above the proportional limit, bending stresses do not vary linearly across a section, because stress is not proportional to strain. The stress distribution computed on the basis of the flexure formula

$$\sigma = \frac{Mc}{I} \;\ldots\ldots\; (6.3)$$

is shown by the dotted line. The extreme straight-line fiber stresses computed on the basis of this formula are seen to be greater than the true maximum fiber stresses.

6.2 Bending Test Data

Most structures and machines have members whose primary function is to resist loads that cause bending. Examples are beams, hooks, plates, slabs columns under eccentric loads. The design of such of structural members may be based upon tensile compressive and shear properties appropriately used in various bending formulas. In many instances, however bending formulas give results which only approximate the real conditions. While special analysis can often be made of stresses arising from unusual loading conditions and from local distortions and discontinuities, it is not always feasible to make such analysis, which may be very complicated. The bending test may serve than as a direct means of evaluating behavior under bending loads, particularly for determining the limits of structural stability of beams of various shapes and sizes.

Flexural test on beams are usually made to determine strength and stiffness in bending; occasionally they are made to obtain a fairly complete picture of stress distribution in a flexural member. Beam tests also offer a means of determining the resilience and toughness of materials in bending.

In most of steel constructions and machine members made of welding are also subjected to bending. For example, the casing structure of a steel construction joined together by welding and all of the weld seams on this structure are subjected to bending and in most cases bending is the most critical loading. Because of all these reasons the data obtained from the formulas do not give the exact solutions so the welded parts shall be checked by also bending test.

Under the general designation of strength may be included the proportional limit, yield strength, and modulus of rupture. These properties may be determined with a view to establishing, with appropriate reduction factors, allowable bending stresses for use in design. The modulus of rupture may also be used simply as a criterion of quality in control tests.

The stiffness of a material may be determined from a bending test in which the load and deflection are observed. The modulus of elasticity for the material in flexure is computed by use for an appropriate deflection formula. The value of the modulus of elasticity may then be used to compute the elastic deflection of beams of the same material but of other size, shape, or loading, although some error may be involved owing to ignoring shearing deflections, which are of importance in short, deep beams; deviations from the straight-line relationship of stress and strain as expressed by Hooke's Law; and lack of uniformity of the material.

Because the loads required to cause failure may be relatively small and easily applied, bending tests can often be made with simple and inexpensive apparatus. Because the deflections in a bending test are many times the strains in a tension test, a reasonable determination of stiffness or resilience can be made with less sensitive and less expensive instruments than are required in a tension test.

In the welded parts, by applying the load three points and causing bending, a tensile force acts on the material opposite the midpoint. Fracture begins at this location. The flexural strength, or modulus of rupture, describes the material strength:

$$FlexuralStrength = \frac{3FL}{2wh^2} \quad \text{.........} \ (6.4)$$

where F is the fracture load, L is the distance between two outer points, w is the width of the specimen and h is the height of the specimen.

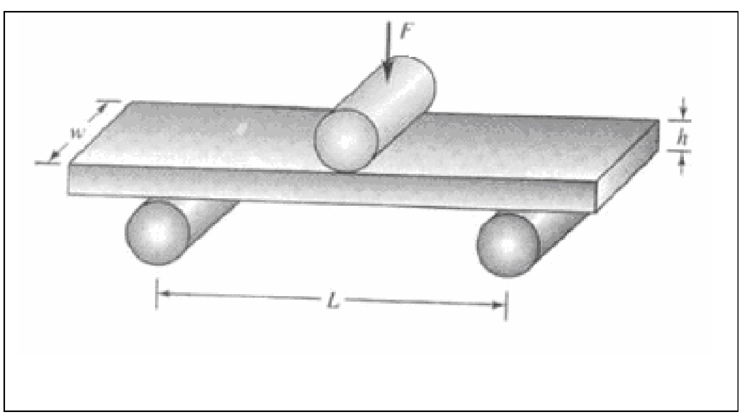


Fig. 6.5: Three-Point Bending

The modulus of elasticity in bending, or the flexural modulus is calculated in the elastic region of Fig. 6.6:

$$FlexuralModulus = \frac{L^3 F}{4wh^3 \delta} \quad \ldots\ldots\ldots (6.5)$$

where δ is the deflection of the beam when a force F is applied.

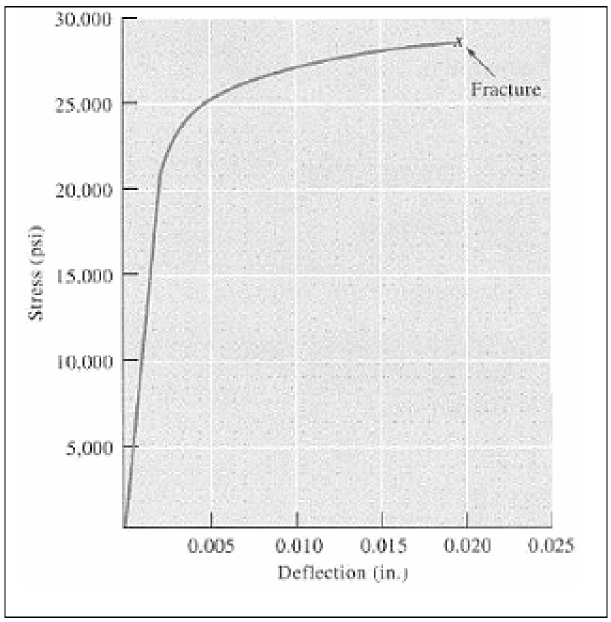


Fig. 6.6: Stress-Deflection Curve

6.3 Types of Bending Test

Some of the more common methods carrying out bend tests are illustrated in the following paragraphs. The basic requirements of the bend test, as defined above, are met by the simple arrangement of Fig. 6.7

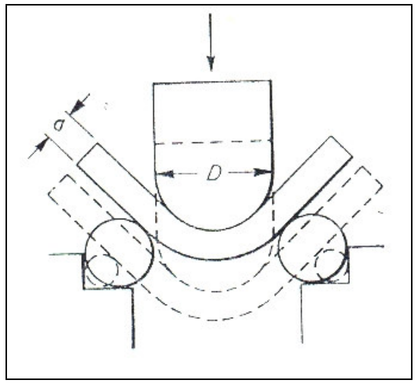


Fig. 6.7: Bending Test Arrangement

The test piece is laid on two parallel supports and bent by pressure applied through the mandrel at the center. The mandrel is usually of hardened steel, and it is customary to use a mandrel having a radius equal to that specified as the internal radius round which the test piece is to be bent. If during bending the test piece remains in contact with the "nose" of the mandrel round an appreciable arc, this particular requirement is met. The criterion for passing the test is normally the absence of any cracks which can be seen by the unaided eye, so that visual inspection of the outside of the bend after removing the test piece from the machine completes the test.

Rounding the edges of the supports is necessary, but the radius is an arbitrary dimension. As the test piece bends it is drawn over these edges; if the edges were too sharp they would damage the test piece and impede the movement. On the other hand, frictional forces here help to keep the test piece in contact with the roller and tend to prevent to peaking. A test piece is said to "peak" when it suffers a very severe deformation over a short length at the middle, where it losses contact with the mandrel. The internal radius of the bend test piece may then be very much less than that of the mandrel; the severity of the test is greatly increased.

The reasons for peaking are not clearly understood, but some materials are less prone than others to behave in this way, and for these it is possible, by a simple modification to the form of the supports, to cater for tests of materials of different thickness, while using a single fixed pair of supports and insert rollers of various diameters.

These are the details of the bending test for welded parts, the dimensions of the bending test specimen and the dimensions of the bending test machines will be given in detail in the related section.

The types of bending test for welded parts will be explained in the following paragraphs.

6.3.1 Nick-Break Test

The specimens shown in Fig. 6.8 are used to conduct a nick-break test.

The prepared specimen is placed on supporting members as illustrated in Fig. 6.8 and a load applied until the piece breaks. The surface of the fracture is then examined for porosity, gas pockets, slag inclusions, overlap, penetration, and grain size. For an accurate check of the soundness of the weld the fractured pieces should be subjected to an etch test.

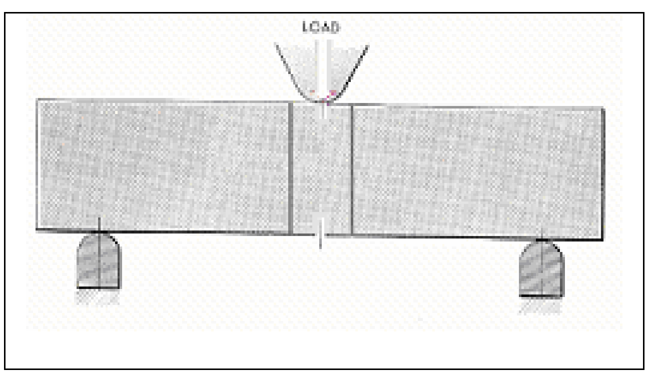


Fig. 6.8: Nick-Break Test

6.3.2 Free-Bend Test

This test is particularly valuable to ascertain the ductility of a weld. A test piece is cut from the plate to include the weld. The top of the weld is ground or machined so it is flushed with the base metal surface. The scratches produced by grinding should run across the weld in the direction of the bend as indicated in Fig. 6.9. If the scratches extend along the weld they might cause premature failure and give incorrect results, because they act as stress raisers.

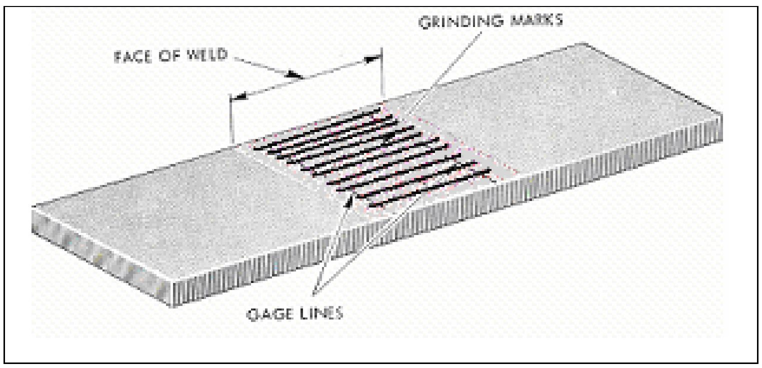


Fig. 6.9: Free-Bend Test

The distance across the weld is layed out as in Fig. 6.9 and lightly marked with a prick punch. The piece is bent by hammering in the vise with the face containing the gage lines on the outside of the bend, or by imposing load. After the specimen is given a permanent set the final bend is made. When the bend is completed the distance between the gage lines measured.

6.3.3 Guided-Bend Test

For this test two specimens are required. One piece referred to as the face-bend specimen is used to check the quality of fusion; that is, whether the weld is free of defects such as porosity, inclusions, etc. The second piece referred to as the root-bend specimen is used to check the degree of weld penetration.

The test is conducted by placing the face-bend specimen in a guided-bend jig face down and bending until it forms U-shape. If upon examination, cracks greater than “0.2 x width of the specimen” appear in any direction the weld is considered to have failed.

In the root-bend test the specimen is placed in the jig with the root down or in just the reverse position of the face-bend piece. The results must also show no cracks to be acceptable.

In the thesis, a similar bending test is applied by using the tensile testing machine. The same procedure given above is applied by means of a round mandrel and fixed supports. This configuration will be explained in the following sections. By this type of bending test the welded part is subjected to the loads in accordance with the principle given in the Section 6.1.1. The details of the dimensions and application procedure will be explained in the related sections.

6.4 Bending Test Machine

As mentioned above in this thesis project, three point bending method is used to check the welds and their strength performance. In three-point bending there are two rollers to carry the test specimen and a moving mandrel to bend the test piece from the welded portion. Generally in three-point bending a universal tensile testing machine is used. The tensile testing machine, which was used in the tensile testing, was also used in bending test.

In the bending test, tensile testing machine is occupied with two rollers and a loading block (mandrel) with certain diameters which are determined by the related standards. The supports with rollers are used not to produce defects on the surface of the specimen while bending and their diameters are chosen according to this basic criterion to prevent peaking by producing enough friction. Also the diameter of the roller to chosen to produce stable loading and not to cause any defect on the surface of the specimen. The test arrangement will be given in the following parts, which is obtained from the related standard EN 910 and DIN 50121 “technological Bending Test on Welded Joints and Weld Platings”.

The principal requirements of the supporting and loading blocks for beam tests are as follows:

- They should be of such shape that they permit use of a definite and known length of span.
- The areas of contact with the material under test should be such that unduly high stress concentrations (which may cause localized crushing around the bearing areas) do not occur.
- There should be provision for longitudinal adjustment of the position of the supports so that longitudinal restraint will not be developed as loading progress.
- There should be provision for some lateral rotational adjustment to accommodate beams having a slight twist from end to end, so that torsion stresses will not be induced.
- The arrangement of parts should be stable under load.

6.5 Bending Test Specimen

6.5.1 Sampling

Sampling is a very important step of all test procedures. The samples should be prepared in such a way that they could easily realize the working conditions in the test area.

In this thesis project the welded parts, the tensile test and bending test specimens are prepared according to EN 288-3 “Specification and Approval of Welding Procedures for Metallic Materials – Part 3: Welding Procedure Tests for The Arc Welding of Steels” and EN 910 respectively. In these standards all details of the welding procedure and testing of the welded parts are explained. According to the above mentioned standards bending test specimens are obtained from the certain places of the welded part.

In addition to this surface quality of the welded part and removal technique of the bending specimen from the welded part are given in the related standard EN 910. In the EN 910 also the dimensions of the bending test specimen are given. All of these properties will be explained in the following paragraphs.

6.5.2 Sampling for Welded Parts

All the data given in this section is obtained from the related standards EN910 and DIN 50121. By using these standards the bending test specimens are prepared. Under the following subtitles the dimensions and their short explanations will be given item by item.

6.5.2.1 Thickness of the Specimen

For transverse root and face bend tests the test specimen thickness, a, shall be equal to the thickness of the base material adjacent to welded joint. As mentioned in the Section 1, the thickness of the welded parts are 20 mm, therefore, the thickness of the specimen shall be 20 mm.

6.5.2.2 Width of the Specimen

In plates, for transverse root or face bend tests, the width of the specimen is determined according to the material of the welded part. In thesis project all welded parts are made of steel. According to the standard EN 910, for steel, the width, b, of the test specimen shall not be less than 1.5 times a, with minimum of 20 mm. Therefore, the width of the specimen is calculated by using the formula given below;

$$b \geq 1.5a \quad \rightarrow \quad b \geq 1.5 \times 20 \Rightarrow \quad b = 30mm$$

6.5.2.3 Radius of the Specimen Edges

The edges of the test specimen on the face in tension shall be rounded by mechanical means to a radius “r” not exceeding 0.2a to a maximum of 3 mm. In our case a equals to 20 mm, therefore, r equals to 4 mm, however, r cannot exceed 3 mm. According to the above mentioned explanation, r is chosen as 3 mm.

6.5.2.4 Radius of Rollers

As mentioned in the Section 6.4, the bending test machine is occupied with roller supports. These supports have a certain diameter that, not to cause peaking on the specimen. According to DIN 50121-2 our test machine has a roller with diameter of 40 mm.

6.5.2.5 Length of Specimen (L_t)

The length of the specimen is given in the EN 910 with the equation given below;

$$L_t \geq l + 2R$$

where, l is the distance between the rollers and r is the radius of the rollers. The distance between the rollers was 100 mm and the radius of the rollers was 20 then L_t was calculated as 140 mm. However, as mentioned in EN 910 while choosing the dimension application standard should also be considered then DIN 50121-2 was checked for the total length of the specimen. In DIN 50121-2 total length of the specimen is given as; $L_t \geq 225$ mm. Therefore, $L_t = 280$ mm is an appropriate dimension for the total length of the bending test specimen.

6.5.3 Removal of Test Specimens

The test specimen shall be removed transversely from the welded joint in such a way that, after machining the weld axis will remain in the middle of the parallel length of the test specimen.

Shearing is excluded for thickness of more than 8 mm. If thermal cutting or other cutting methods which could affect the cut surfaces are used to cut the test specimen from the welded plate, or from test piece, the cuts shall be made at a distance greater than or equal to 8 mm from the surfaces of the width of the test specimen. Thermal cutting shall not be used parallel to the original surface of the welded plate or of the test piece. In the thesis project, all specimens were removed from the welded plate by using a sawing machine and to protect the weld seam from heat deposition of cutting the specimens were cut 8 mm wider than their original dimensions.

The final stages of preparation shall be performed by machining or grinding, suitable precautions being taken to avoid superficial strain hardening or excessive heating of the material. The surfaces shall be free from scratches or notches transverse to the test specimen direction in width. The surfaces of the test specimen shall be machined in such a way that, all excess weld metal is removed.

After all these preparation steps, bending test specimens were ready for testing and the details of application of bending test is given in Section 7.4.2.

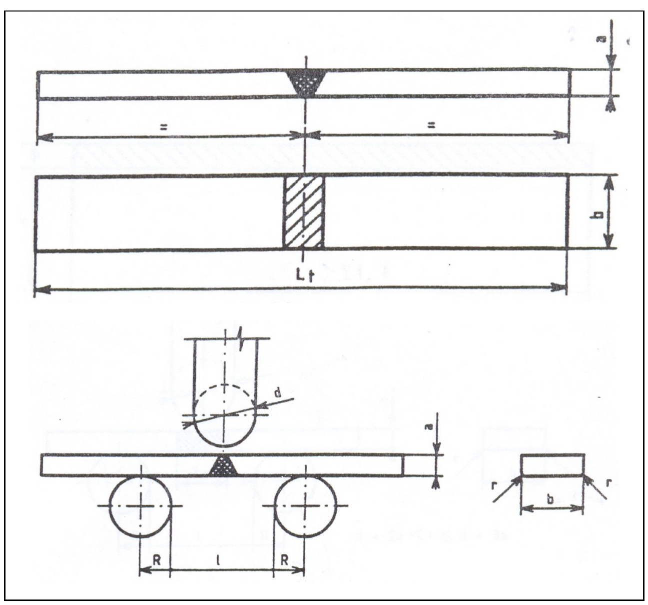


Fig. 6.10: Bending Test Specimen

CHAPTER 7

TESTING AND RESULTS

In this section, a detailed procedure of the tests performed throughout this thesis will be summarized. Up to this section, the theoretical fundamentals and their explanations have been given. In scientific projects practical application is also very important. Therefore, the details of the application of the steps will be explained in this section.

7.1 Welding

Since the main objective of the thesis is to determine the relationship between the welding quality and strength, welding is a very important step of the study. Therefore, welding was done with high sensitivity and after a detailed preparation and comprehensive literature survey. In welding, different kinds of parameters affect the outcome. These can be listed as; material, welding quality, welding method, welding procedure and personnel.

At the beginning of the thesis, the materials that were used in the thesis had been determined. In selecting material, different criteria were considered. In addition, the opinions of different welder firms were taken into account. After the investigation in the welding industry, it was understood that in steel constructions St37, St44 and St52 were the most frequently used steel types. This was due to their good price, good machinability and strength properties. Due to of these properties, St37, St44 and St52 were chosen for investigation in this study.

Another factor affecting the material selection was the wall thickness. During our investigation, since radiographic examination and ultrasonic examination would be used to determine the weld quality, the material thickness has to be convenient for the application of these techniques. As mentioned earlier, it is very important for the objective of this thesis to select the most frequently used steels with preferred thickness and welding techniques in the industry. Due to these reasons a thickness of 20 mm was considered as appropriate for the aim of this work.

Material type and thickness affects other parameters in welding. After material selection, another important subject is welding quality. In EN 25817 "Arc-Welded Joints in Steel – Guidance on Quality Levels for Imperfections", four different weld quality levels are defined. These are; A (with the agreement of parties), B, C and D. A is the quality level that is used only with the agreement of the parties and for special welding work. Since, it is difficult to achieve this quality level and it increases the welding cost, it is only used for special constructions such as space technology, etc.

In this thesis, B and C quality levels were chosen for weld quality. To achieve quality level B, most of the weld defects should not be present and the defects such as gas porosity and worms should be in small size. As mentioned above, to achieve the aim of the thesis by using the most frequently used conditions in the industry, one of the weld quality level was chosen as B. In practice, except the special cases, high quality means weld quality level of B and for steel constructions, boilers, tanks, pressure vessels and etc. quality level of B is required. In the thesis, by choosing the quality level of B it is intended to achieve the same conditions with practical applications as possible.

Comparison of strength values of different quality levels is the most important step of the thesis. Therefore, weld quality level C was chosen as the second quality level. Level C is also frequently used in industry and it is generally used in the welded constructions where high manufacturing quality is not required. When EN 25817 is checked, it will be seen that the weld defects that can be found in the welded parts having the quality level C have bigger dimensions than that of B. A table taken from 25817, which shows the permissible limit of imperfections, can be seen as Table 2.3 at page 38 of Section 2.

After determining the material and welding quality level, welding method was chosen. In this selection the welding method, material and welding quality was kept in mind. The welding method which would yield quality levels B and C with the materials St37, St44 and St52 was determined. Before making the final decision, different methods were tried on the above mentioned materials. During the investigation made in the industry, it was observed that the GMAW (Gas Metal Arc Welding) and SMAW (Shielded Metal Arc Welding) methods were the most frequently used methods on these materials. However, the material thickness is another important parameter in the welding method and GMAW welding method cannot achieve the required quality levels when it is applied on 20 mm thick steels. As a result it was decided to use the SMAW, and the Welding Procedure Specification (WPS) given as an annex was written. In this WPS necessary information about the welding procedure can be seen for both of the quality levels. Also the technical details of the welding method are given in Section 2.

The preparation of specimens for welding is explained below:

i) The 20 mm thick plates were obtained from the market in 150 mm x 600 mm size. These were cut to this dimension from a standardized steel sheet by using oxyacetylene flame. Since at the end of the welding the dimension of the part should be 300 mm x 600 mm as given in the standard 288-3 "Specification and Approval of Welding Procedures for Metallic Materials – Part3", two pieces of 150 mm x 300 mm were joined together by using the written welding procedure.

ii) In the second step, edge of the parts, which would be welded, was prepared according to the standard EN 29692 "Metal-Arc Welding with Covered Electrode". In this standard V shaped welding is proposed for these materials. This V shaped welding can be seen in the Fig.7.1.

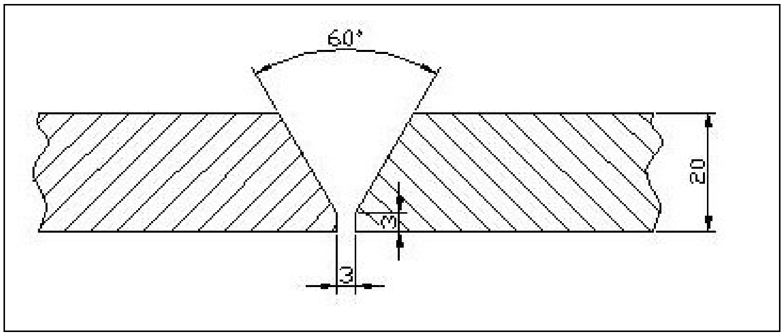


Fig.7.1: V Shaped Welding

While preparing the parts for welding, machining process was used. Machining should be done very carefully because its quality directly affects the weld quality. As given in the WPS, preparation and cleaning should be done carefully by grinding without over heating.

iii) After preparation of the parts, welding was done according to the procedure given in Welding Procedure Specification.

After welding, all specimens (9 specimens with quality level B and 9 with quality level C) were examined by using non-destructive examination methods to determine whether they fulfill the respective quality levels.

Fig. 7.2: Welded Plate

7.2 Radiographic Examination

7.2.1 Examination Conditions

In this section, the selection of examination conditions from the related standard EN 1435 "Non-Destructive Examination of Welds – Radiographic Examination of Welded Joints" is explained.

At the beginning of radiographic examination, some important examination conditions (testing variables) such as; maximum X-ray voltage, film class, screen type, minimum source to object distance, type of penetrameters and some other conditions were determined. The definitions of the parameters used for examination conditions are also given in the standard EN 1435.

First of all, the exposure arrangement is chosen from EN 1435. Since our test piece is a butt-welded plate, the most appropriate test arrangement is the one given in Fig.1 at page 9 of EN 1435. This arrangement is sketched below from the standard (Fig.7.2).

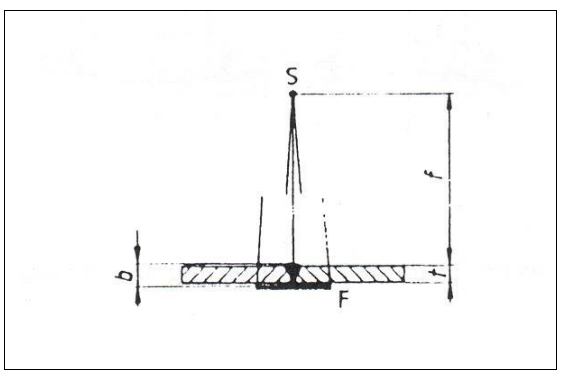


Fig. 7.3: Radiographic Test Arrangement

In the second step, the maximum X-ray voltage was determined. For this purpose the graph given in EN 1435, (pg.17, Fig.20) was used. From this figure the maximum X-ray voltage was determined according to the penetrated thickness and material. For 20 mm thick steel the maximum X-ray voltage can be determined as 280 kV. Therefore, the 300 kV X-ray source in METU laboratory was used during the radiographic examination. During the test, the X-ray voltage was used as 260 kV, because decreasing the X-ray voltage increases the image quality.

After this step, the film system class was selected from Table 2 given at page 20 of EN1435. From this table, the film system class was chosen as C5 according to the radiation source, penetrated thickness and test class. For AGFA, this corresponds to D7 film.

Table 7.1: Butt Joint in Plates and Pipes

<table>
<tr><th rowspan="2">Radiation Source</th><th rowspan="2">Penetrated Thickness w</th><th colspan="2">Film System Class</th><th rowspan="2">Type and Thickness of Metal Screens</th></tr>
<tr><th>Class A</th><th>Class B</th></tr>
<tr><td>X-Rays potentials ≤100 kV</td><td rowspan="3"></td><td rowspan="3">C5</td><td rowspan="2">C3</td><td>None or up to 0.03 mm front and back screens of lead</td></tr>
<tr><td>X-Rays potentials >100 kV to 150 kV</td><td>Up to 0.15 mm front and back screens of lead</td></tr>
<tr><td>X-Rays potentials >150 kV to 250 kV</td><td>C4</td><td>0.02 mm to 0.15 mm front and back screens of lead</td></tr>
<tr><td rowspan="3">X-Rays potentials >250 kV to 500 kV</td><td>w ≤ 50 mm</td><td rowspan="3">C5</td><td>C4</td><td>0.02 mm to 0.2 mm front and back screens of lead</td></tr>
<tr><td rowspan="2">w > 50 mm</td><td rowspan="2">C5</td><td>0.1 mm to 0.2 mm front screens of lead</td></tr>
<tr><td>0.02 mm to 0.2 mm back screens of lead</td></tr>
</table>

In addition to this, also the type and thickness of the metal screen was determined from the same table given above. According to the radiation source, penetrated thickness and film system class, the type and thickness of the metal screen was determined as "0.02 mm to 0.2 mm front and back screens of lead". During testing, 0.02 mm thick front and back lead screens were used to improve the image quality.

Determination of minimum source-to-object distance (f min) is also very important, because this affects the geometrical unsharpness of the exposure. The f min value is determined according to the object-to-film distance and the source size. In our examination object-to-film distance was approximately 25 mm and the size of the source was 1.5 mm, therefore from EN 1435, the f min was determined as 230 mm.

After determining the f min, the film-focus-distance was calculated by the equation given below;

$$FFD \geq f\ min + 20 \quad \text{.....(Eq. 7.1)}$$

When the f min value was used in Eq. 7.1, FFD value was calculated as;

$$FFD \geq 230 + 20 \rightarrow FFD \geq 250\ mm.$$

As the following step, optical density of the radiograph was determined. This examination condition was also determined from EN 1435. For the test class A, the optical density should be at least 2.0 with and a measuring tolerance of ± 0.1.

For the evaluation of image quality, the Image Quality Indicators (IQI) should be used. In our thesis, we used wire type IQI and form EN 1435 the image quality number is found as W11.

The exposure value is obtained from the chart Eresco 300 X-ray unit, which is specified for to the conditions given below;

- B_o = 2.8 mA min

- Focal spot size d = 1.5.mm
- Tube current I = 5 mA (constant)
- Film Type; D7
- Screen; 0.02mm lead screen
- Density; D=2

Since the actual test conditions differed from the above conditions the exposure time is corrected; using the equation given below;

$$B_n = B_o \left(\frac{FFD_n}{FFD_o} \right)^2 \left(\frac{D_n}{D_o} \right) \left(\frac{Ff_n}{Ff_o} \right) \quad \text{.........(Eq.7.2)}$$

where B_o : old exposure value

B_n : new exposure value

FFD_o : old film-focus distance

FFD_n : new film-focus distance

D_o : old optical density

D_n : new optical density

F_{fo} : old film factor

F_{fn} : new film factor

If the old and new values of the above parameters are substituted in the Eq.7.2, the new exposure value is calculated as;

$$B_n = 2.8 \left(\frac{800}{700} \right)^2 \left(\frac{2}{2} \right) \left(\frac{2.5}{1} \right) = 9.14 \quad mA\,\text{min}$$

From above the exposure time is calculated by using the simple equation.

$$t = \frac{B_n}{I} \quad \text{.........(Eq.7.3)}$$

$$t = \frac{9.14[mA\min]}{5[mA]} = 1.83 \quad \min$$

As a summary, exposure conditions for radiographic examination are listed below;

- Test Class: A
- X-ray Voltage: 260 kV
- Film System Class: D7
- Screen: 0.02 mm x 0.02 mm lead
- f_{min} = 230 mm
- FFD≥ 250mm
- Optical Density: D≥2
- Wire IQI: W11
- t = 1.83 min

7.2.2 Film Processing

After taking the film from the X-Ray room, it is processed for evaluation with processing chemicals suitable for the film type. Processing is a very important stage for image quality, film density and sensitivity. The type and concentration of developer, the timing of process steps and some other conditions affect the processing. For example, if the concentration of developer is less than the proper level, then this causes an important problem of low optical density and if the optical density is less than the required value given in EN 1435, then the radiograph is not acceptable, it should be rejected. Films were developed for 5 minutes at 20ºC. The remaining steps were carried out accordingly.

7.2.3 Evaluation of Radiographs

After processing, the radiograph was evaluated on a special viewing device (illuminated screen). At the beginning of evaluation the optical density was measured by a densitometer. For an acceptable radiograph, the optical density on the weld seam should be at least equal to the optical density value given in EN 1435. Also, to meet the image quality requirement, at least 10 mm of the IQI wire should be seen on the radiograph. If the required optical density and image quality number is reached than the film is evaluated for the defects.

In this thesis, we want to check the test specimens, whether they meet quality level B or C. For this purpose, during the evaluation, the type, size and frequency of permissible defects are compared with the radius given in standard EN 25817 and then the specimens were classified according to their quality levels. Results of the radiographic examination can be seen as a tabular data given in Table 7.2. The photographs given in figures Fig.7.4 and Fig.7.5 show the results of the radiographic examination for B and C quality levels.

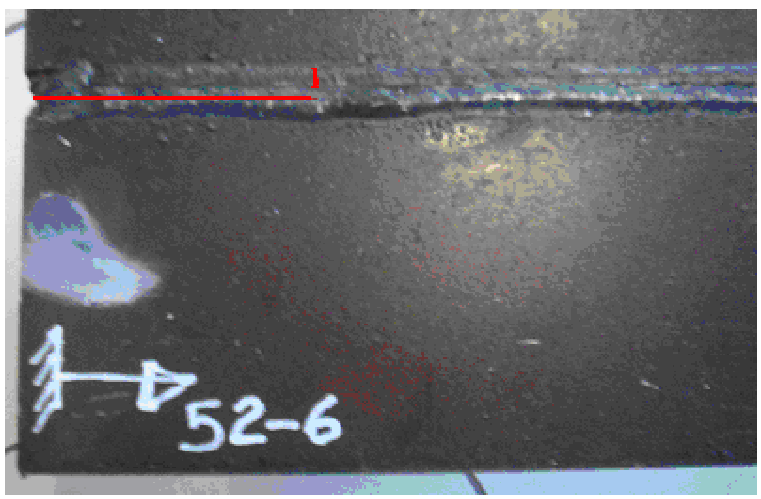


Fig 7.4: Reference Point for Radiographic Examination

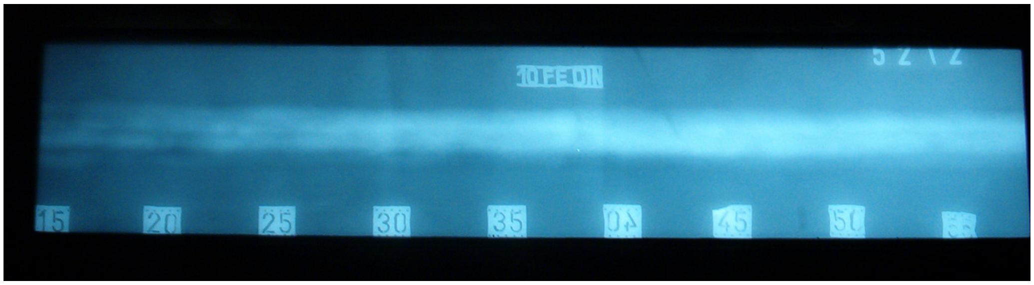


Fig.7.5: Radiographic Film of Quality Level B

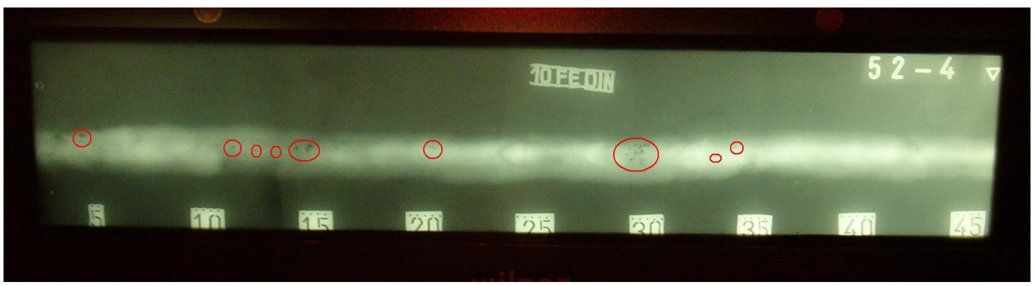


Fig.7.6: Radiographic Film of Quality Level C

Table 7.2: Results of Radiographic Examination

		Defect			
Part No.	**Material**	**Type**	**Position acc. to reference point (mm)**	**Size (mm)**	**Quality Level**
37-1	St 37	There is no defect on the weld seam	N/A	N/A	B
37-2	St 37	There is no defect on the weld seam	N/A	N/A	B
37-3	St 37	There is no defect on the weld seam	N/A	N/A	B
37-4	St 37	Gas pores	210	1	C
	St 37	Gas pores	300	1	C
	St 37	Gas pores	410	1	C
	St 37	Gas pores	450	2	C

Table 7.2 continued

37-5	St 37	Gas pores	180-210	1	C
	St 37	Gas pores	360-370	1	C
37-6	St 37	Gas pores	130-140	1	C
	St 37	Gas pores	260-280	1	C
	St 37	Gas pores	420-440	1	C
44-1	St 44	There is no defect on the weld seam	N/A	N/A	B
44-2	St 44	There is no defect on the weld seam	N/A	N/A	B
44-3	St 44	There is no defect on the weld seam	N/A	N/A	B
44-4	St 44	Gas pores	30	1	C
	St 44	Gas pores	60	1	C
	St 44	Gas pores	100-120	1	C
44-4	St 44	Gas pores	150	1	C
	St 44	Gas pores	170-200	1	C
	St 44	Gas pores	100	1	C
	St 44	Gas pores	135	1	C
	St 44	Gas pores	200	1	C
	St 44	Gas pores	220	1	C
	St 44	Gas pores	230	1	C
	St 44	Gas pores	370-400	1	C
	St 44	Gas pores	460-490	1	C
44-6	St 44	Gas pores	200-250	1	C
	St 44	Gas pores	380-400	1	C
52-1	St 52	There is no defect on the weld seam	N/A	N/A	B
52-2	St 52	There is no defect on the weld seam	N/A	N/A	B
52-3	St 52	There is no defect on the weld seam	N/A	N/A	B
52-4	St 52	Gas pores	30-70	1	C
	St 52	Gas pores	100-200	1	C
	St 52	Gas pores	290-350	1	C
	St 52	Gas pores	420-550	1	C
52-5	St 52	Gas pores	50-120	1	C
	St 52	Gas pores	150-200	1	C
	St 52	Gas pores	240-350	1	C
	St 52	Gas pores	390-410	1	C
52-6	St 52	Gas pores	440-480	1	C

After radiographic examination, all welded specimens were subjected to ultrasonic examination.

7.3 Ultrasonic Examination

The Ultrasonic Examination was the second non-destructive examination technique used in the thesis. This is done to detect any defects which may not be detected by radiography. As mentioned in other section determination of weld quality is very important for our study and the weld quality should be B or C level given in EN 25817, otherwise the relationship between the weld quality and strength will not be true.

7.3.1 Distance Calibration

Ultrasonic testing device should always be calibrated before each examination. For this calibration skip sonic distance (S_p) and time-base range for sonic distance (S_B) were calculated, and by using these values and calibration block K2 the calibration table was prepared.

The skip sonic distance was calculated by using the formula given below;

$$S_p = \frac{2d}{\cos\alpha} = \frac{40}{\cos 60} = 80 \quad mm$$

S_p is 80 mm. In this formulation d is the thickness of the welded part, α is the angle of incidence of the probe used. Angle of incidence of probe is an important parameter to determine the defects on the weld seam. If the probe angle is not chosen properly than it may cause misleading results. Weld angle is one of the most important criteria to determine the probe angle α. In our study the weld angle is 60º as seen in Fig.7.1, therefore, the best probe for this case is 60º also. In our study a miniature probe with 60º is used. Also the frequency of the probe should be chosen properly and it is chosen from EN 1712 "Non-Destructive Examination of Welds –

Ultrasonic Examination of welded Joints – Acceptance Levels" as 4 MHz according to the material thickness. S_B was calculated as;

$$S_B \cong 1.2 \times S_p \cong 1.2 \times 80 \cong 96 \quad mm$$

$$S_B = 100 \quad mm$$

Table 7.3: Calibration Table

S(mm)	**T(div)**	**Echo**
25	2.5	F1
100	10	F2

After determination of S_B a calibration table was prepared and using the signals obtained in this table, the ultrasonic testing device was calibrated.

By using the ultrasonic testing device calibrated according to the calibration table given above, DAC and DGS curves were drawn.

Before the ultrasonic examination, one of the methods given in EN 1712 and EN 1714 "Non-Destructive Examination of Welds – Ultrasonic Examination of welded Joints" should be chosen. These methods are called as DAC (Distance Amplitude Curve) and DGS (Distance Gain Size). These curves are the reference curves which are drawn by using different method. In DAC method, the DAC curve is drawn by using the holes drilled according to the standard EN 583-2 "Non-Destructive Testing – Ultrasonic Examination – Part 2: Sensitivity and Range Setting". However, in DGS method, the readily prepared curve drawn by the manufacturer of the ultrasonic probe draws reference curve. Generally DGS is the most frequently used technique because of its easy use. In our thesis for the correct determination of defects and weld quality both of the methods (DAC and DGS) were used. Now, let's talk about the theoretical fundamentals and drawing procedure of DAC and DGS curves.

7.3.2 DGS Curve

These were first formalized by J. Krautkrämer in 1958 and consist of plots of amplitude in decibels from a series of disc-shaped reflectors, with increasing distance of probe, obtained in water. They are derived theoretically, and if plotted with distances in terms of the near-zone length, can be of general form, applicable to all probes. The loss due to water attenuation is allowed for, so the curves show data for any material, assuming no attenuation. DGS diagrams can also be derived for particular probes.

For drawing the DGS curve the reference curve given by the probe manufacturer and the part, which has the holes drilled for DAC curve were used. When the drilled part is used, the sensitivity of the DGS curve will increase therefore, there will be no deviation caused by difference in the density of the material and by this way the most exact DGS curve will be obtained.

At the beginning of DGS drawing, diameter of the disk shaped reflector (DSR), which necessary for the DGS curve, was determined from EN 1714, page 10, Table-3 as 1.5 mm (Table 7.4). As mentioned above the drilled part, which was prepared for DAC curve, was used also for drawing the DGS. While drawing the DGS curve the hole with diameter of 3 mm and with the depth of 15mm was used because there was no DSR on the related part. Under these circumstances, by using the formula given below the hole with diameter of 3 mm would be converted theoretically into a DSR.

Table 7.4: Reference Levels for Longitudinal Waves for DGS

Nominal Probe Frequency (MHz)	Thickness of Parent Material (mm)		
	$8 \leq t < 15$	$15 \leq t < 40$	$40 \leq t \leq 100$
1.5 to 2.5	-	D_{DSR} = 2 mm	D_{DSR} = 3 mm
3 to 5	D_{DSR} = 1 mm	D_{DSR} = 1.5 mm	-

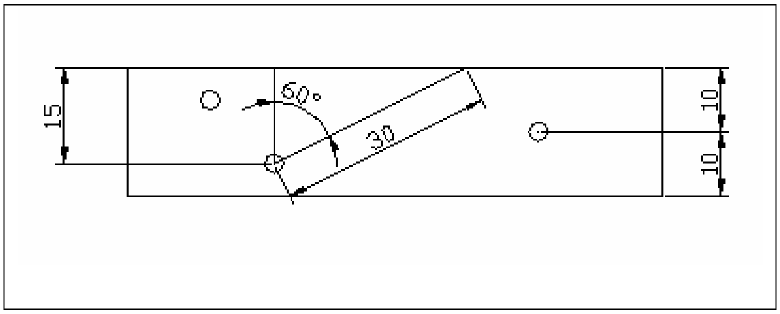


Fig. 7.7: Drilled Part Used for DGS Curve Sensitivity Setting

$$D_{DSR} = \sqrt[4]{0.2\lambda^2 D_{SDH}\, s}$$

Where

D_{DSR} : Diameter of disk shaped reflector

λ : Wave length

D_{SDH} : Diameter of side-drilled hole

s : Shortest distance between the test surface and hole (15 mm)

$$s = \frac{15}{\cos 60} = 30 \quad mm \Rightarrow s = 30 \quad mm$$

D_{SDH} = 3 mm

$$\lambda = \frac{v}{f} = \frac{3255 \quad m/s}{4 \quad (1/s)} = 0.81 \quad mm \Rightarrow \lambda = 0.81 \quad mm$$

$$D_{DSR} = \sqrt[4]{0.2 \times (0.81)^2 \times 3 \times 30} = 1.85 \quad mm \Rightarrow D_{DSR} \cong 2 \quad mm$$

As a result of these calculations diameter of DSR was found as 1.85 mm but taken as 2 mm. The reference DGS diagram of the probe was prepared for the diameter range between 1.5 mm and 2mm and if D_{DSR} were used as 1.85 mm then deviation from the real case would increase, therefore, D_{DSR} were taken as 2mm.

In the third step, the intersection point of S_B = 100 mm and D_{DSR} = 1.5 mm was pointed on the reference curve given by the probe manufacturer and gain value was read from the graphic as 36 dB and this gain value is called as reference gain value. Then the point of intersection of S_j = 30 mm and D_{DSR} = 2 mm was pointed on the same curve and V_j , which was the gain value at S_j, was found as 18 dB. Then by using the formulas given below, the additional gain value (ΔV) and working gain value (V_R) are found as follows;

$$\Delta V = V_k - V_j = 36 - 18 = 18 \text{ dB} \Rightarrow \Delta V = 18 \text{ dB}$$

$$V_R = V_v + \Delta V = 24 + 18 = 42 \text{ dB} \Rightarrow V_R = 42 \text{ dB}$$

where V_v is the gain value obtained from the ultrasonic test machine for the hole of 15 mm depth at 80% screen height.

After these calculations V_R = 42 dB would be used as working gain value during the ultrasonic examination.

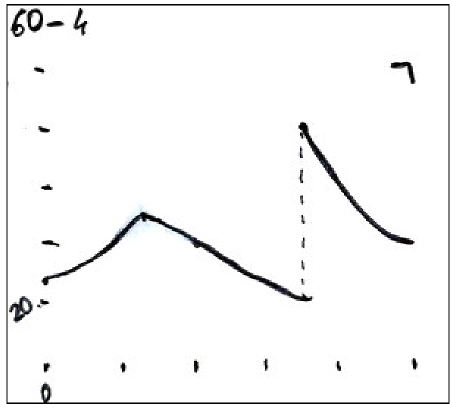


Fig. 7.8: DGS Diagram

The obtained DGS curve was a “Method 2” reference curve and it would be used in the ultrasonic examination of the welded parts. While the ultrasonic examination evaluation and record levels defined in the related standards were used.

7.3.3 DAC Curve

Simple theory states that for a flaw of a given size and shape in the far zone of the probe, neglecting absorption effects, the echo height from the flaw varies inversely as the square as the distance of the flaw from the probe. It possible to provide an amplifier circuit which can correct for the flaw distance effect, but in the view of the complications due to absorption and scatter, it is more usual to use an accurately linear amplifier and provide a DAC curve; sometimes this DAC curve is superimposed on the cathode-ray tube screen. With the advent of computer controlled ultrasonic equipment, distance-amplitude corrections can be applied automatically with a suitable program.

A suitable type of test block for preparing a DAC curve will be outlined in this Section, the procedure being to adjust the probe position for a maximum echo from each hole in turn, having set the gain to obtain 80% of full-scale height from the hole. The sensitivity setting at which the DAC curve was obtained must be recorded.

In strongly attenuating material, it may be necessary to add a correction factor for attenuation.

With both flat-bottomed holes and side-drilled holes, it is not easy to obtain constant results, particularly with broad-band probes, due to the non-constant relationship between wavelength and target size.

As defined in EN 1714, for DAC curve the side drilled holes (SDH) with a diameter of 3 mm were used. The distance between the holes and the depth of holes are specified in EN 583-2. According to this standard, bearing the thickness of the material in mind it was decided to drill two holes given below. Since, the distance between the holes are not given in EN 583-2, "AD-Merkblatt HP 5/3-NDE Methods for Pressure Vessels" was used to determine this distance.

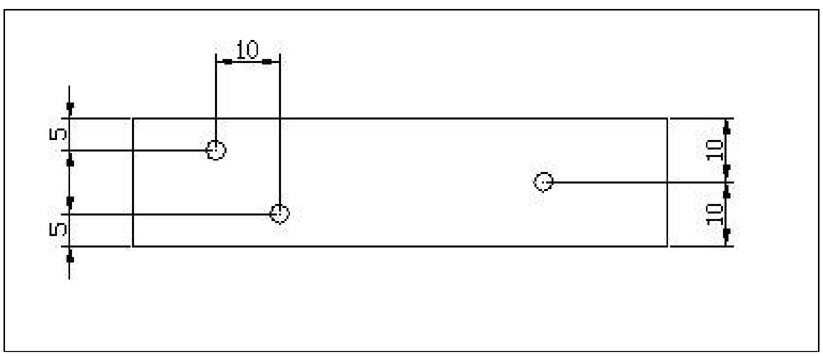


Fig. 7.9: DAC Holes Sketch

$$b = S_j - 10 = 20 - 10 = 10 \text{ mm} \Rightarrow b = 10\text{mm}$$

where, S_j is the thickness of the welded plate.

After determining the diameters, distance and the length of the holes should be determined and EN 583-2 was used for this purpose. In EN 583-2 the formula given below is given for the length of the holes;

$$e \rangle \frac{2\lambda S}{D_{eff}} \ldots(7.4)$$

where, λ is the wave length (mm), s is the sonic distance (mm), D_{eff} is the effective diameter of the probe.

As mentioned earlier, in our study, a 60º miniature probe is used for the ultrasonic examinations, which has rectangular cross-section with dimensions 8 x 9 mm. For these kinds of probes, effective probe diameter is found by using the below formula.

$$D_{eff} = 0.95 \times 9 = 8.55 \quad mm \ldots(7.5)$$

In addition to this, sonic distance, S was found by the calculations given below;

$$x = \frac{5}{\sin 30} = 10 \quad mm \Rightarrow x = 10 \quad mm$$

$$S_{p/2} = \frac{S_p}{2} = \frac{\frac{2d}{\cos\alpha}}{2} = \frac{20}{\cos 60} = 40 \quad mm \Rightarrow S_{p/2} = 40 \quad mm$$

$$S_1 = x + S_{p/2} = 10 + 40 = 50 \quad mm \Rightarrow S_1 = 50 \quad mm$$

However, if s were taken as 80 mm, more accurate result for the length of the hole would be obtained, because the maximum S distance while the ultrasonic wave propagation was about 80 mm. When all these data put in equation (7.4), the required length of the holes was found as 15 mm.

After the hole-preparation step, DAC curve was drawn by using the ultrasonic test device.

At first theoretical calculations were done. In these calculations direct and indirect sonic distance are determined. The distance between the hole and the test surface is called as direct sonic distance. The distance between from test surface to distance from the S_p of hole is called as indirect sonic distance. For all materials 3 direct and 2 indirect sonic distance were calculated. By this way different points for the maximum screen width S_B = 100 mm were determined. These direct and indirect points are listed below. For St 37, St 44 and St 52 the direct and indirect sonic distance list is same.

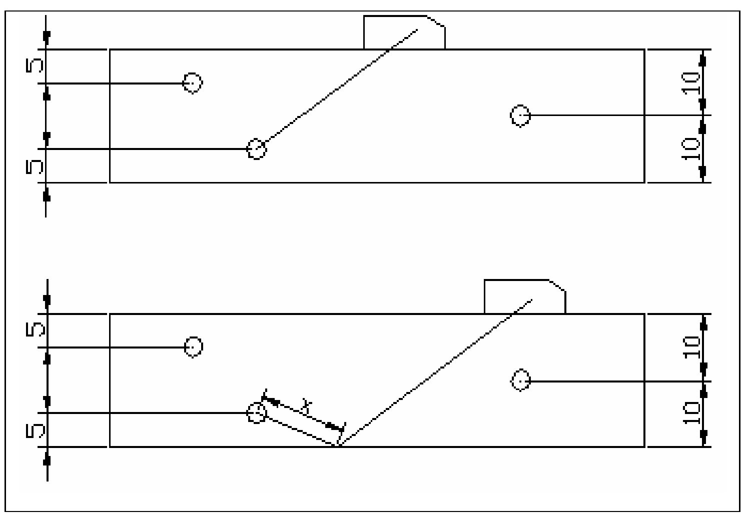


Fig. 7.10: Direct and Indirect Sound Attenuation

For St 37, St 44 and St 52

Direct → 5 mm → S = 5 / sin30 = 10 mm

Direct → 10 mm → S = 10 / sin30 = 20 mm

Direct → 15 mm → S = 15 / sin30 = 30 mm

Indirect → 30 mm → S = 30 / sin30 = 60 mm

Indirect → 50 mm → S = 50 / sin30 = 100 mm

The second step in drawing the DAC curve was making the control for each of the points listed above with probe. The aim of this control is to determine the highest echo and the hole that causes this echo. The point (direct or indirect) where the highest echo was determined, the height of the echo was adjusted to 80% screen height by using the switches of the ultrasonic testing device and the dB value read from the ultrasonic testing device was recorded. The list of the maximum points determined for each material is given below.

For St 37;

Direct → 5 mm → S = 5 / sin30 = 10 mm → 80 %, 45 dB

For St 44;

Direct → 5 mm → S = 5 / sin30 = 10 mm → 80 %, 42 dB

For St 52;

Direct → 5 mm → S = 5 / sin30 = 10 mm → 80 %, 40 dB

These values are called as V_R which means working gain value. The recorded dB value was adjusted on the ultrasonic testing device and then for each direct and indirect point given above screen heights were determined and pointed on the transparent screen. After these steps the points were joined together like a 3rd order curve and at the end DAC curve was obtained.

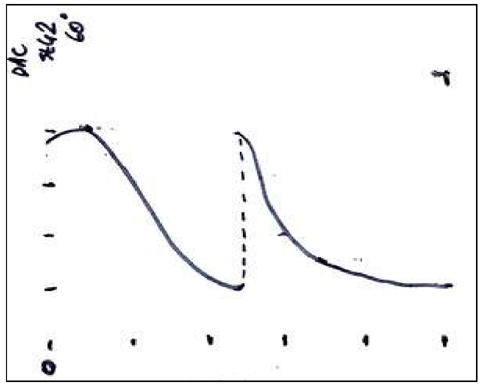


Fig 7.11: DAC Curve

7.3.4 Ultrasonic Testing

After drawing the DAC and DGS curves, all parts should be tested by ultrasonic examination. However, the distance that would be used while the examination to determine the possible defects in the examination area defined in the related standard should be determined. This distance is called as scanning zone width and while the examination the probe will be moved in the range of distance. Scanning zone width was determined by using the formula given below.

$$Scanning\ \ Zone\ \ Width = S_p + 10 - x$$

In this formula S_p is the skip sonic distance and x is probe index and it is 12 mm for the probe used during the examination. Therefore,

$$Scanning\ \ Zone\ \ Width = 80 + 10 - 12 = 78 \cong 80\ \ mm$$

was the scanning zone width. From this calculation it was understood that the probe should be moved in the range of 80 mm at both side of the weld seam.

After this final calculation we started to the ultrasonic examination. In ultrasonic examination first step is application of coupling. At first the testing surface of the welded part was covered with oil, which was used as coupling material. Covering process was done in the distance of 160 mm (80 mm for each side of weld seam). In the covering the most important parameter is the thickness of the coupling material. If the coupling layer is thinner or thicker than the required then some of the weld defects will be overlooked, therefore, the thickness of the coupling layer should be enough to increase the interface surface between the probe and the testing surface and wave propagation.

After the application of coupling material, DAC or DGS curve drawn previously was put on the screen of the ultrasonic testing device. After adjustments, probe was moved smoothly on the surface of the welded part. The range of this movement is restricted by scanning zone width and the movement path of the probe can be seen from the sketch given below.

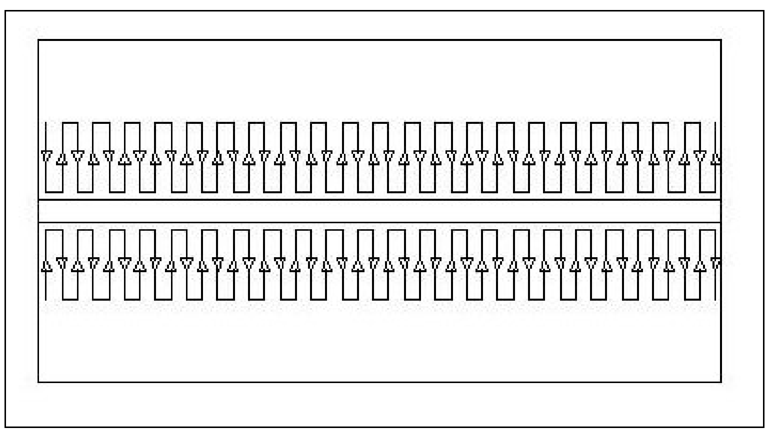


Fig. 7.12: Prop Movement for Ultrasonic Testing

While these movements screen of the ultrasonic testing device was always checked and the signal was always followed either it passes the reference curve or not. In this case, if the DAC or DGS curve was passed then this point was recorded and the place and dimensions of defect was determined. For this determination a table is prepared and in this table the distance of the defect from the weld seam and recording dB value are given. By using these data it is possible to determine the place and dimension of the defect exactly.

Table 7.5: Recommended Examination Levels

Examination Level	Quality Level in EN 25817
A	C
B	B
C	by agreement
D	special application

For the determination of scanning directions and probes EN 1714 standard is used. In EN 1714, different examination levels for different kinds of welding are given. Weld quality levels given in EN 25817 play important role in the determination of examination level. By using the Table 7.5 (Table-5 given at page 12 of EN 1714), the examination levels related with the weld quality levels were determined. In accordance with this table, for weld quality level of C, the examination level of A and for weld quality of B, examination level of B was used in ultrasonic examination. If all these data are combined with thickness of the welded part the scanning directions can be determined. According to EN 1714, both sides of the welded part were examined from both side of the weld seam, therefore the scan number was four in our thesis project.

In the light of these explanations all welded specimens were examined ultrasonically and the weld quality levels determined by radiographic examination were checked.

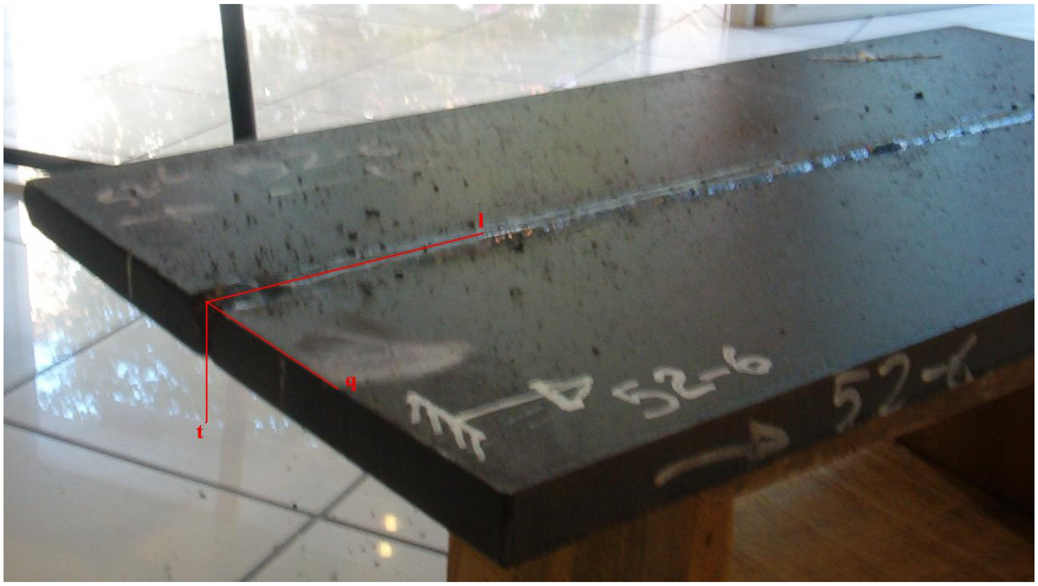


Fig. 7.13: Reference point for Ultrasonic Examination

Table 7.6: Ultrasonic Results

				Position acc. to reference axis (mm)			
Part No.	**Method**	**Material**	**Type**	**l**	**q**	**t**	**Quality Level**
37-1	DAC	St 37	No Defect	-	-	-	B
	DGS	St 37	No Defect	-	-	-	B
37-2	DAC	St 37	No Defect	-	-	-	B
	DGS	St 37	No Defect	-	-	-	B
37-3	DAC	St 37	No Defect	-	-	-	B
	DGS	St 37	No Defect	-	-	-	B
37-4	DAC	St 37	Gas pores	230	16.38	9.69	C
		St 37	Gas pores	310	16.02	12.99	C
	DGS	St 37	Gas pores	225	19.68	8.66	C
37-5	DGS	St 37	Gas pores	200	24.68	8.66	C
		St 37	Gas pores	350	16.02	12.99	C
		St 37	Gas pores	352	-9.02	12.99	C
	DAC	St 37	Gas pores	350	-1.38	9.69	C
	DGS	St 37	Gas pores	350	10.04	14.02	C
37-6	DGS	St 37	Gas pores	243	-8.70	18.35	C
		St 37	Gas pores	425	-8.31	13.15	C
		St 37	Gas pores	427	16.02	12.99	C

Table 7.6 (continued)

37-6	DAC	St 37	Gas pores	268	-6.02	12.99	C
		St 37	Gas pores	280	5.04	14.02	C
44-1	DAC	St 44	No Defect	-	-	-	B
	DGS	St 44	No Defect	-	-	-	B
44-2	DAC	St 44	No Defect	-	-	-	B
	DGS	St 44	No Defect	-	-	-	B
44-3	DAC	St 44	No Defect	-	-	-	B
	DGS	St 44	No Defect	-	-	-	B
44-4	DGS	St 44	Gas pores	180	-10.70	18.35	C
		St 44	Gas pores	150	1.02	12.99	C
		St 44	Gas pores	185	8.42	14.29	C
	DAC	St 44	Gas pores	185	9.29	13.86	C
	DGS	St 44	Gas pores	185	11.02	12.99	C
		St 44	Gas pores	110	-20.35	10.83	C
44-5	DGS	St 44	Gas pores	100	-5.04	14.02	C
		St 44	Gas pores	205	8.89	19.05	C
	DAC	St 44	Gas pores	375	6.02	12.99	C
44-6	DAC	St 44	Gas pores	230	-3.04	14.02	C
		St 44	Gas pores	385	-11.72	5.36	C
52-1	DAC	St 52	No Defect	-	-	-	B
	DGS	St 52	No Defect	-	-	-	B
52-2	DAC	St 52	No Defect	-	-	-	B
	DGS	St 52	No Defect	-	-	-	B
52-3	DAC	St 52	No Defect	-	-	-	B
	DGS	St 52	No Defect	-	-	-	B
52-4	DGS	St 52	Gas pores	50	-4.37	16.18	C
		St 52	Gas pores	125	-6.70	18.35	C
		St 52	Gas pores	155	-0.04	14.02	C
		St 52	Gas pores	52	4.37	16.18	C
		St 52	Gas pores	135	6.77	14.89	C
	DAC	St 52	Gas pores	50	-3.70	18.35	C
52-5	DGS	St 52	Gas pores	260	8.70	18.35	C
		St 52	Gas pores	390	8.70	18.35	C
	DAC	St 52	Gas pores	105	-2.64	15.32	C
		St 52	Gas pores	265	-10.23	16.62	C
	DGS	St 52	Gas pores	52	13.19	0.60	C
		St 52	Gas pores	154	33.11	10.56	C

From these results it is clearly seen that some of the defects which could be determined by radiographic examination cannot be determined by ultrasonic examination. According to these results we cannot say that radiographic examination is more reliable than ultrasonic examination. Generally different NDE methods are not used as alternatives of one another. However, in certain cases one of the techniques may give more accurate results than the others.

7.4 Mechanical Tests

The scope of mechanical tests was limited to; tensile and bending tests. These tests were applied according to the related standards. The test specimens to be used for mechanical tests are prepared from the welded and nondestructively examined plates.

The application of the mechanical tests will be explained in the following sections.

7.4.1 Tensile Testing

Tensile testing is one of the most frequently used mechanical tests and it gives very important data about the strength of the material. In addition to this, tensile testing is also used for the approval of Welding Procedure Specification (WPS) in other words it is used for the preparation of Welding Procedure Approval Record (WPAR) and this case is explained in EN 288-3 in detail.

Tensile testing specimens for welded parts were prepared according to the EN 895 “Destructive Tests on Welds in Metallic Materials – Transverse Tensile Test” as explained in Section 5. To prevent heat deposition on the specimen, saw cutting was used to remove the specimens from welded plates and they were cut 8 mm wider from both sides to be on the safe side. Therefore, the specimens were cut 16 mm wider than the specified dimension. After cutting, the test specimens were machined into required dimensions by milling machine. The machining process is done to decrease the dimension from 53 mm to 37 mm.

Fig. 7.14: Saw Cutting

The last step of machining was surface preparation and milling machine processed both of the surfaces of the tensile test specimen. In surface finishing the aim is to equalize the root and the cap of the weld seam with the base metal.

The final dimensions of the subject tensile test specimen are as follows;

- Thickness of the Test Specimen (a) = 20 mm
- Width of the Calibrated Parallel Length (b) = 25 mm
- Width of the Shoulder (b_1) = 37 mm
- Parallel Length (L_c) = 80 mm
- Radius of Shoulder (r) = 30 mm
- Maximum Width of the Weld After Machining (L_S) = 20 mm
- Total Length of the test Specimen (L_t) = 280 mm.

After these preparation steps each specimen was subjected to tensile testing according to the related standard. The details of the application procedure will be explained in the following paragraphs.

First of all, the original gauge length was marked on the specimen, by this way the percent elongation after the test could be determined. The thickness and the width of the specimen were measured and noted to the test sheet and also these data were entered to the computer of the test machine.

The most important point of mounting the specimen to the test machine is the linearity. If the test specimen is not connected between the grips in parallel, certain amount of bending stress occurs on the test piece and this directly affects the test results such as lower yield strength, upper yield strength and tensile strength. This important point is also restricted by the related application standards.

At the beginning of the tensile test the extensometer was put on the specimen. At the yield point the tensile test machine is stopped for the removal of the extensometer.

After fracture, the final gauge length was measured and the percent elongation was calculated. Also by measuring the final width and thickness of the specimen, the final cross sectional area and then the percent reduction in the area was calculated.
At the end of the tensile test, the results such as, tensile strength, lower yield strength, upper yield strength and modulus of elasticity were taken from the computer connected to the tensile testing machine.

Results for each specimen are given in the Table 7.7 and the comments about the relationship between the welding quality and the strength are discussed in the discussion and conclusion section.

In the Table 7.7 maximum tensile load is denoted by F_m, tensile strength is denoted by R_m, upper and lower yield strengths are denoted by R_eH and R_eL respectively. In the subject table "% reduction" also means % Reduction in Area which is one of the important parameter for the ductility.

Fig 7.15: Tensile Test Apparatus

7.4.2 Bending Test

Like tensile testing, bending test is also used for determining the strength properties of the welded parts. Bending test is also used for the approval of Welding Procedure Specification as explained in EN 288-3.

Bending test of welded parts is done according to EN 910 “Destructive Tests on Welds in Metallic Materials – Bend Tests” standard and in this standard dimensions and properties of the bending test specimen are given in detail. The most important point that must be taken into consideration during the preparation of the bending test specimen is to take precautions against the effects of high temperature occurs during cutting that can affect the composition and structure of the weld seam. Therefore, the specimen was cut 16 mm wider than the required dimension from the welded part.

After saw cutting, the specimen was manufactured by using milling machine. 16 mm of width is machined and at the end of machining process the part had original dimension of 30 mm width. As a third step, both of surfaces of the bending test specimen were machined because of the reason mentioned in the tensile test. During bending, on the edge of the bending specimen, which is forced to tension, important and dangerous tension stress occurs. This tension stress is very critical because it may cause sudden crack formation on the edge of the specimen and it directly affects the strength properties of the specimen. Therefore, these edges are rounded with radius given in EN 910 by milling machine and by this way sudden crack formation, uneven stress distribution and sudden deformations are prevented. The final dimensions of the bending test specimen are as follows;

- Thickness of the Specimen (a) = 20 mm
- Width of the Specimen (b) = 30 mm
- Radius of the Specimen Edges = 3 mm.
- Radius of Rollers = 40 mm
- Length of Specimen (L_t) = 280 mm

Initially, mid point of the specimen was marked with permanent pen. By this way the specimen could be mounted to the test machine correctly. From the related application standard DIN 50121-2 "Technological Bending Test on Welded Joints and Welded Platings – Fusion Welded Joints", distance between the rollers was determined as 100 mm and the rollers were installed to the test machine by the way of fastening. This is one of the most critical stages of bending test, if the rollers and specimen are not installed correctly, the correct results from the bending test can not be obtained. Therefore the installation of specimen was done very carefully. As known the guided bend test should be applied from three-point and it is also called as three-point bending, therefore, the installation was done according to the three-point bending principle by using two rollers with diameter 40 mm.

By using the control panel of the test machine, the amount of displacement in unit time was adjusted as 1 mm/sec according to DIN 50121-2. This amount had to be small enough to reach the steady state testing conditions.

The bending test was applied to the specimen until it breaks. During the bending test, maximum bending force was read from the integrated control panel. This force is very important to determine the flexural modulus and flexural strength as mentioned in Section 6. After reading the maximum bending force from the testing machine the flexural strength was calculated by using equations (6.4) and (6.5). All bending test data are given for Face and Root Specimens in tables 7.8 and 7.9 respectively.

In Tables 7.8 and 7.9 maximum bending load is denoted by F_m.

For all test results given in the related tables, graphical demonstrations are prepared and given at pages 130-137.

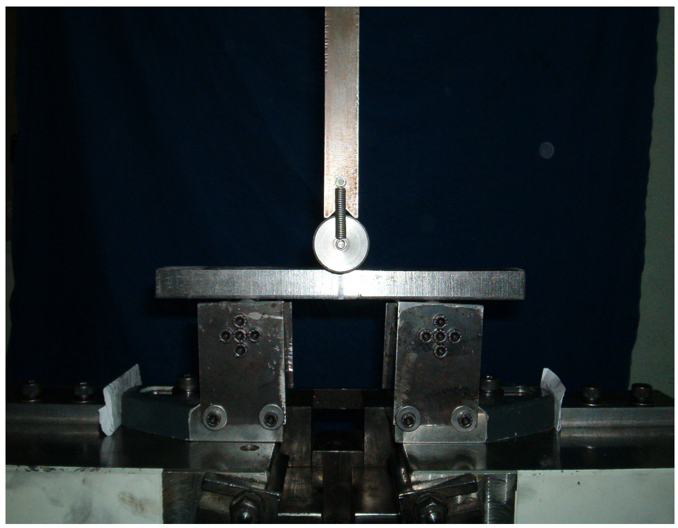


Fig. 7.16: Bending Test Apparatus

Fig. 7.17: Bending Test Specimen after Test

Table 7.7: Tensile Test Results

Specimen No	**Material**	**Specimen Type**	**Weld Quality**	**Weld Defect**	**F_m (kN)**	**R_m (MPa)**	**R_eH (MPa)**	**R_eL (MPa)**	**% Elongation**	**% Reduction**	**Fracture Location**
311	St 37	Tensile	B	N/A	221.5	492	382	360	31	70	OWA
321	St 37	Tensile	B	N/A	214.1	476	351	348	27	54	OWA
331	St 37	Tensile	B	N/A	209.7	456	294	280	24	57	OWA
341	St 37	Tensile	C	Pores	239.8	461	316	308	22	60	OWA
351	St 37	Tensile	C	Pores	238.1	458	288	285	27	58	OWA
361	St 37	Tensile	C	Pores	303	583.1	393	381	32	63	OWA
411	St 44	Tensile	B	N/A	213.7	475	370	363	28	67	OWA
421	St 44	Tensile	B	N/A	219.3	586	449	442	31	64	OWA
431	St 44	Tensile	B	N/A	218.2	551	451	431	27	66	OWA
441	St 44	Tensile	C	Pores	295.9	569	385	381	28	53	OWA
451	St 44	Tensile	C	Pores	304.4	557	372	358	32	54	OWA
461	St 44	Tensile	C	Pores	234.9	452	298	291	29	63	OWA
511	St 52	Tensile	B	N/A	291	582	582	581	31	62	OWA
521	St 52	Tensile	B	N/A	273.6	568	400	383	27	63	OWA
531	St 52	Tensile	B	N/A	287.1	574	402	388	29	65	OWA
541	St 52	Tensile	C	Pores	290.6	559	403	400	31	72	OWA
551	St 52	Tensile	C	Pores	295.6	569	382	317	31	75	OWA
561	St 52	Tensile	C	Pores	292.9	563	383	370	29	72	OWA

N/A: Not Applicable
OWA: Out of Weld Area

Table 7.8: Bending (Face) Test Results

Specimen No	Material	Specimen Type	Weld Quality	Weld Defect	F_m (kN)	% Elongation	Fracture Location	Flexural Strength (MPa)
313	St 37	BF	B	N/A	57.91	9	No Fracture	724
323	St 37	BF	B	N/A	56.63	10	No Fracture	708
333	St 37	BF	B	N/A	59.81	8	No Fracture	748
343	St 37	BF	C	Pores	74.78	N/A	Fracture at weld	935
353	St 37	BF	C	Pores	70.66	N/A	Fracture at weld	883
363	St 37	BF	C	Pores	74.60	10	No Fracture	933
413	St 44	BF	B	N/A	62.10	10	No Fracture	776
423	St 44	BF	B	N/A	60.47	9	No Fracture	756
433	St 44	BF	B	N/A	64.00	10	No Fracture	800
443	St 44	BF	C	Pores	50.29	N/A	Fracture at weld	740
453	St 44	BF	C	Pores	87.60	N/A	Fracture at weld	1095
463	St 44	BF	C	Pores	84.19	N/A	Fracture at weld	1052
513	St 52	BF	B	N/A	78.05	10	No Fracture	976
523	St 52	BF	B	N/A	78.85	9	No Fracture	986
533	St 52	BF	B	N/A	76.35	9	No Fracture	954
543	St 52	BF	C	Pores	71.96	N/A	Fracture at weld	900
553	St 52	BF	C	Pores	77.07	9	No Fracture	963
563	St 52	BF	C	Pores	75.90	N/A	Fracture at weld	949

N/A: Not Applicable
BF: Bending Face Specimen

Table 7.9: Bending (Root) Test Results

Specimen No	Material	Specimen Type	Weld Quality	Weld Defect	F_m (kN)	% Elongation	Fracture Location	Flexural Strength (MPa)
315	St 37	BR	B	N/A	58.60	N/A	No Fracture	733
325	St 37	BR	B	N/A	56.63	N/A	No Fracture	708
335	St 37	BR	B	N/A	62.94	N/A	No Fracture	787
345	St 37	BR	C	Pores	75.95	N/A	No Fracture	949
355	St 37	BR	C	Pores	73.17	N/A	No Fracture	915
365	St 37	BR	C	Pores	76.10	N/A	No Fracture	951
415	St 44	BR	B	N/A	58.89	N/A	No Fracture	736
425	St 44	BR	B	N/A	57.70	N/A	No Fracture	721
435	St 44	BR	B	N/A	55.64	N/A	No Fracture	696
445	St 44	BR	C	Pores	78.85	N/A	Fracture at weld	986
455	St 44	BR	C	Pores	86.08	N/A	Fracture at weld	1076
465	St 44	BR	C	Pores	87.11	N/A	No Fracture	1088
515	St 52	BR	B	N/A	82.72	N/A	No Fracture	1034
525	St 52	BR	B	N/A	80.25	N/A	No Fracture	1003
535	St 52	BR	B	N/A	82.40	N/A	No Fracture	1030
545	St 52	BR	C	Pores	65.92	N/A	Fracture at weld	824
555	St 52	BR	C	Pores	76.49	N/A	Fracture at weld	956
565	St 52	BR	C	Pores	72.37	N/A	Fracture at weld	905

N/A: Not Applicable
BR: Bending Root Specimen

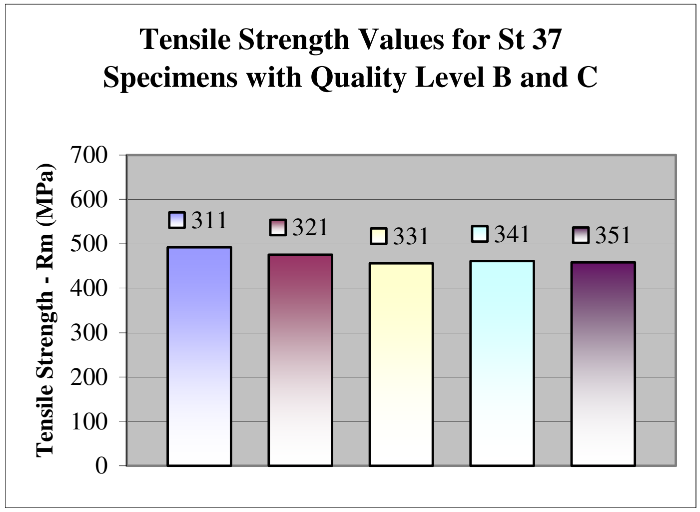


Fig. 7.18: Tensile Strength Values for St 37 Specimens with Quality Level B and C

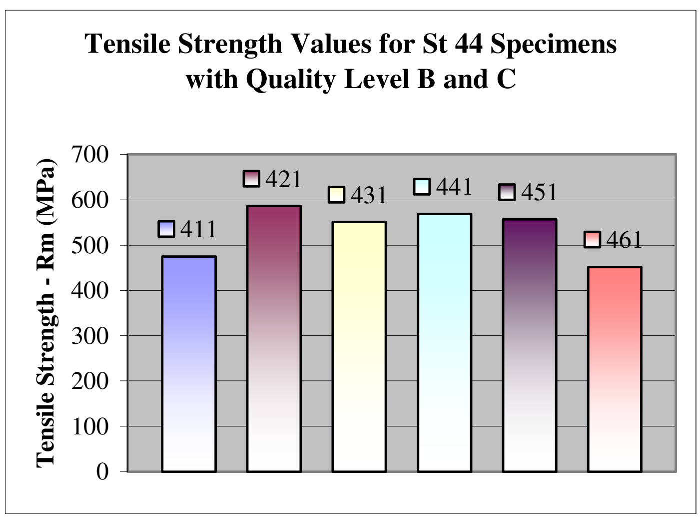


Fig. 7.19: Tensile Strength Values for St 44 Specimens with Quality Level B and C

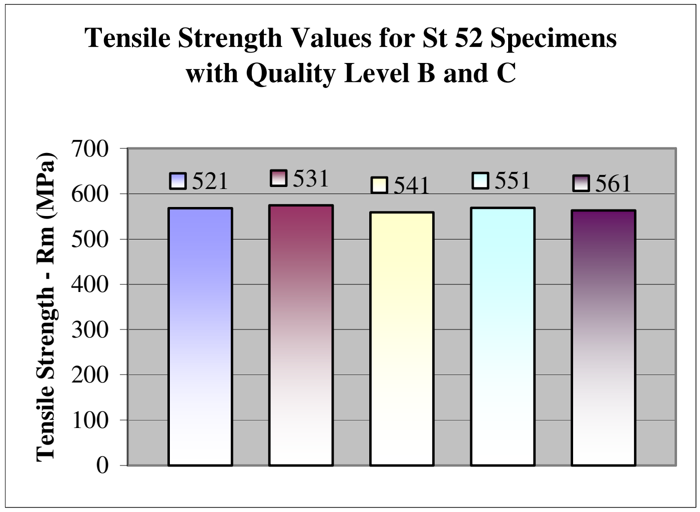
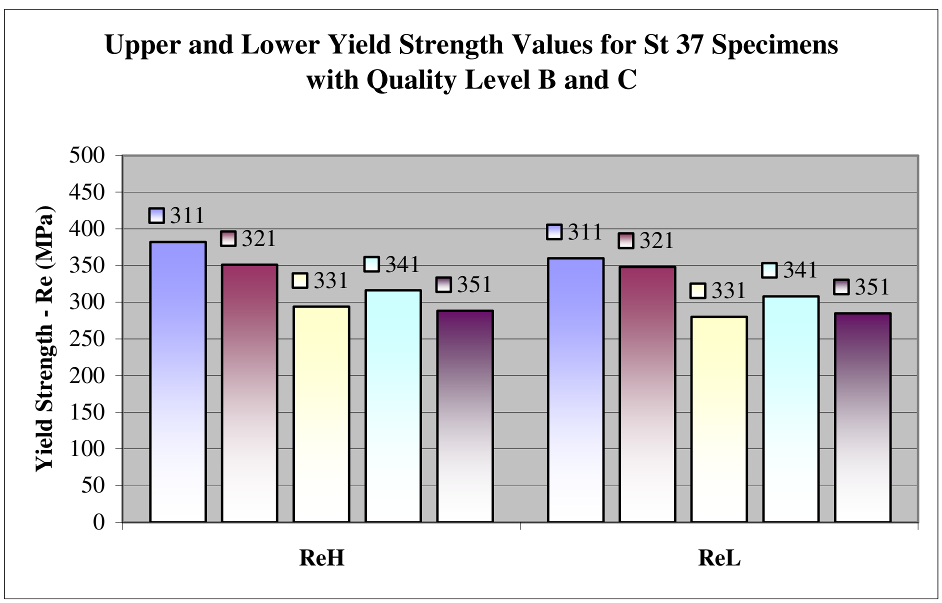


Fig. 7.20: Tensile Strength Values for St 52 Specimens with Quality Level B and C



7.21: Upper and Lower Yield Strength Values for St 37 Specimens with Quality Level B and C

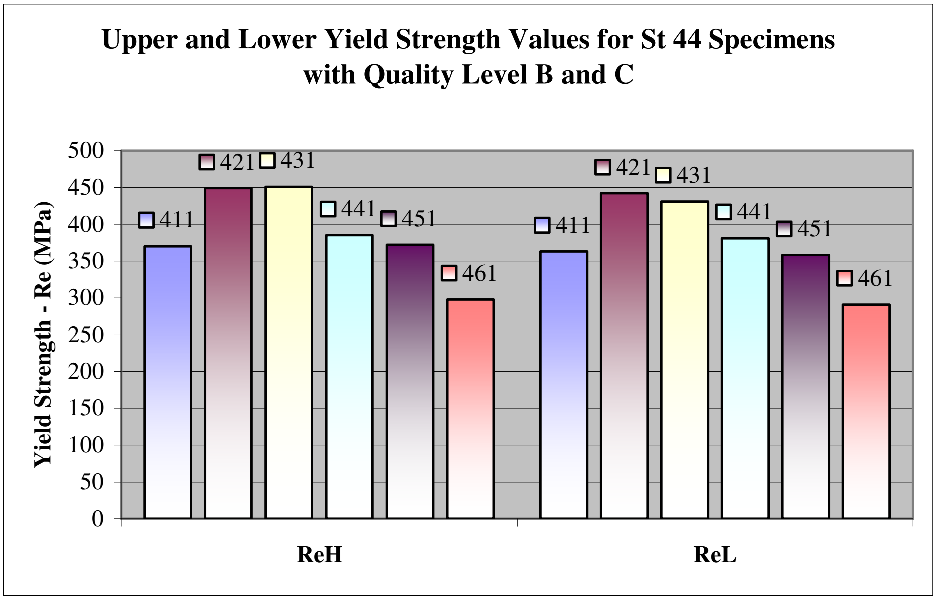


Fig. 7.22: Upper and Lower Yield Strength Values for St 44 Specimens with Quality Level B and C

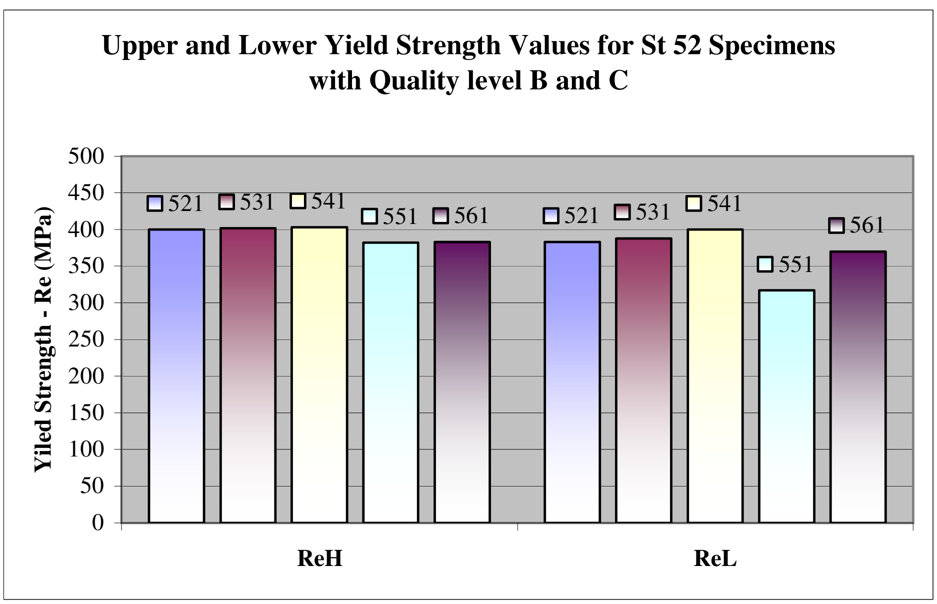


Fig. 7.23: Upper and Lower Yield Strength Values for St 52 Specimens with Quality Level B and C

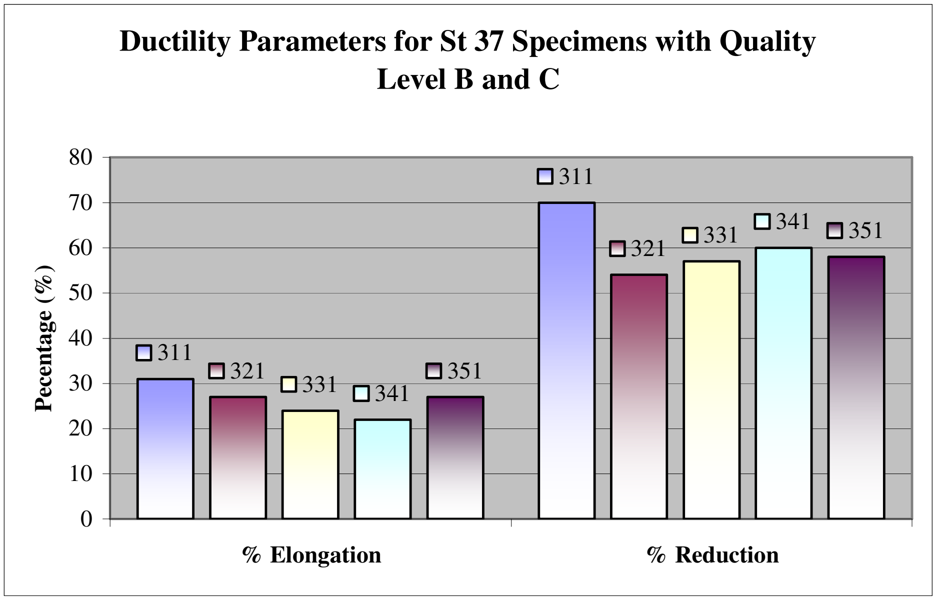


Fig. 7.24: Ductility Parameters for St 37 Specimens with Quality Level B and C

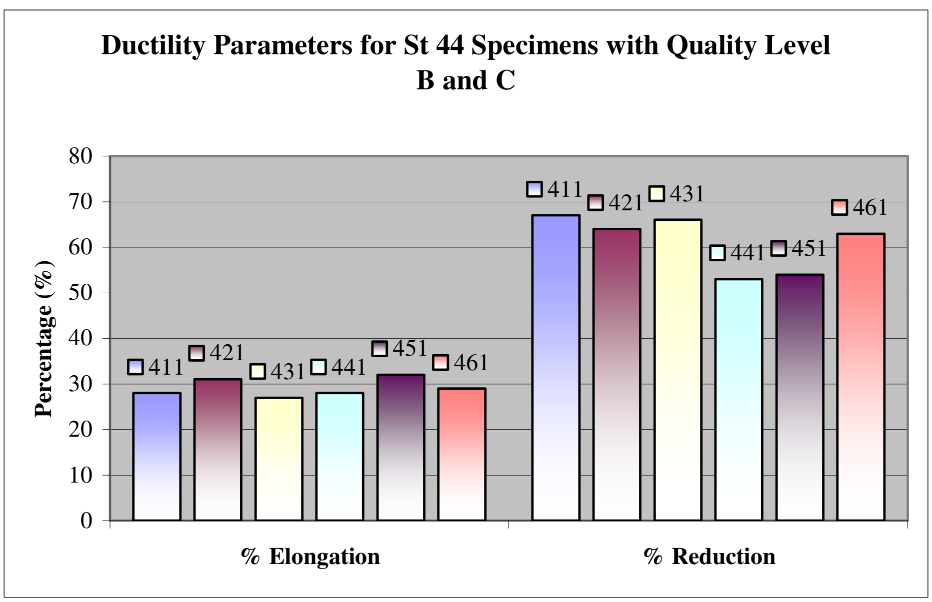


Fig. 7.25: Ductility Parameters for St 44 Specimens with Quality Level B and C

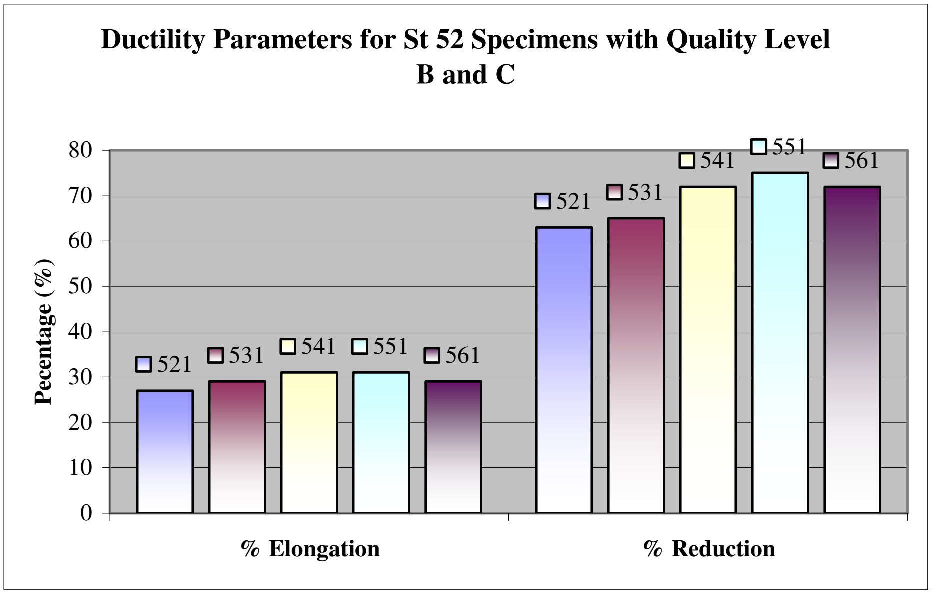


Fig. 7.26: Ductility Parameters for St 52 Specimens with Quality Level B and C

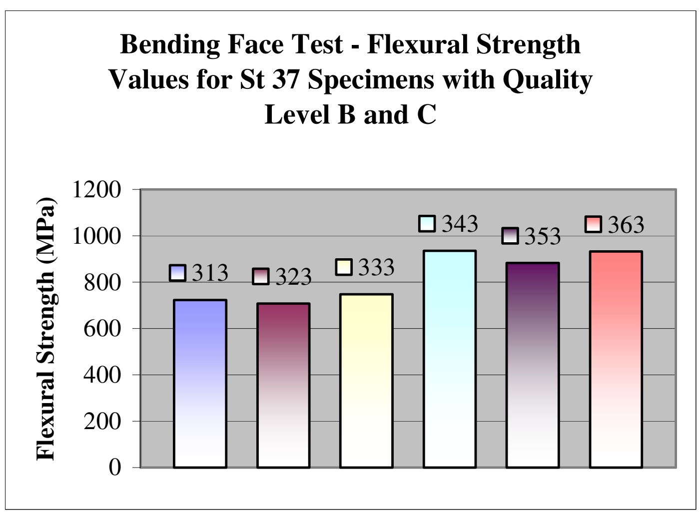


Fig. 7.27: Bending Face Test – Flexural Strength Values for St 37 Specimens with Quality Level B and C

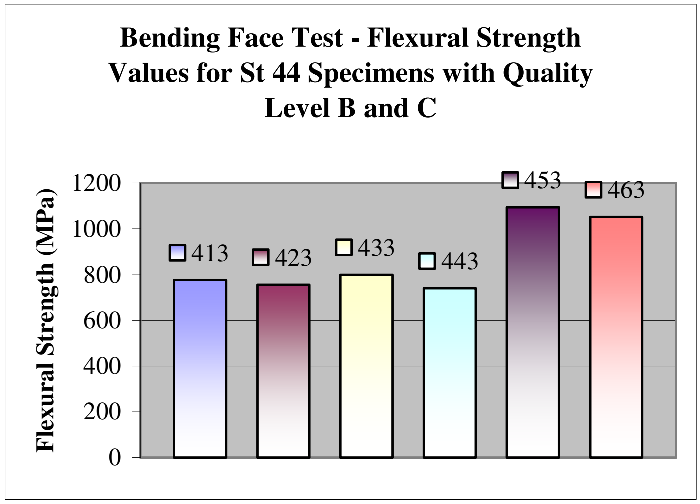


Fig. 7.28: Bending Face Test – Flexural Strength Values for St 44 Specimens with Quality Level B and C

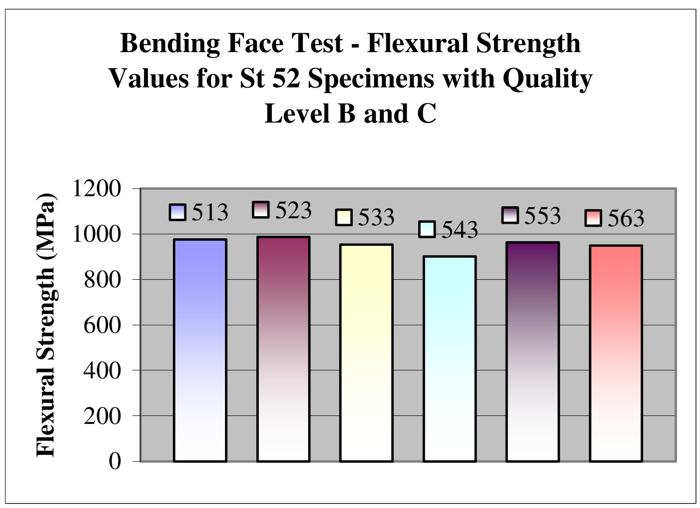


Fig. 7.29: Bending Face Test – Flexural Strength Values for St 52 Specimens with Quality Level B and C

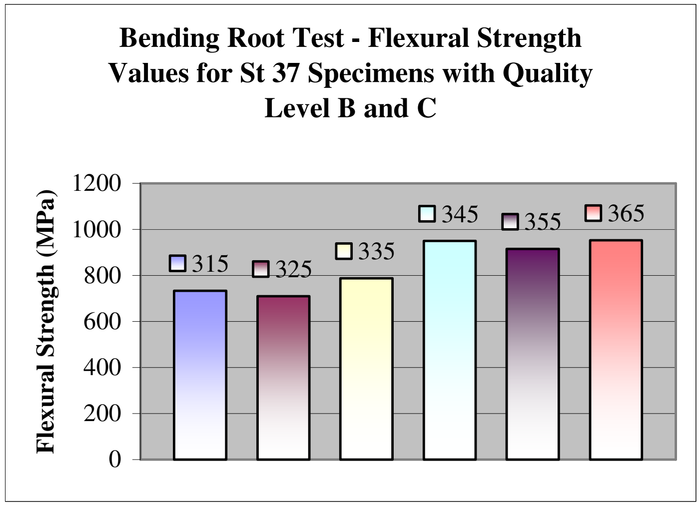


Fig. 7.30: Bending Root Test – Flexural Strength Values for St 37 Specimens with Quality Level B and C

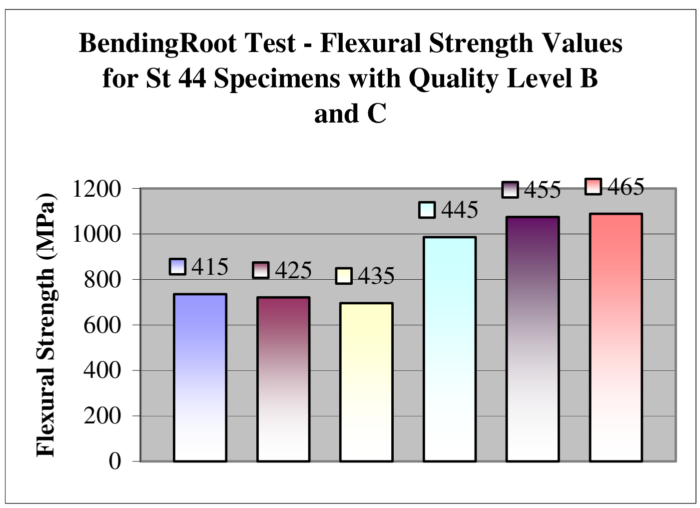


Fig. 7.31: Bending Root Test – Flexural Strength Values for St 44 Specimens with Quality Level B and C

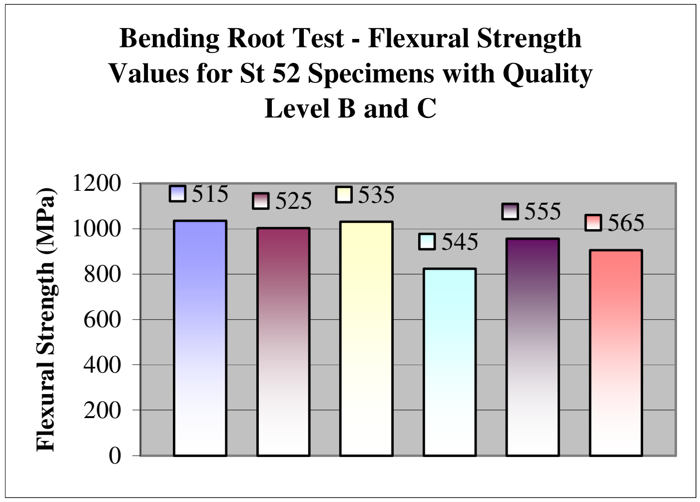


Fig. 7.32: Bending Root Test – Flexural Strength Values for St 52 Specimens with Quality Level B and C

CHAPTER 8

DISCUSSION and CONCLUSION

This chapter will discuss and elaborate the results of non-destructive examination, tensile and bending tests, and will provide a general overview.

8.1 Discussion

8.1.1 Non Destructive Testing Results

When the results of non-destructive examination testing are analyzed, it has been observed that some of the flaws determined with radiographic examination could not be determined with ultrasonic examination. This does not mean that radiographic examination is more reliable than ultrasonic examination, but confirms the generalization that a specific method is more suitable than others in certain cases. In this context, it must not be inferred from the results that a specific method is superior to others.

The most important factor in these results is the complete determination of the problems in the welded pieces and the results obtained from the non-destructive examination demonstrate that the welded parts have gas porosity. Porosity is the cavity type discontinuity formed by gas entrapment during solidification. Specific defects can be called as gas pockets which are gas cavities caused by entrapped gas. These are sometimes called blow holes when they are long and continuous. Porosity is not a serious defect as cracks primarily because porosity cavities usually have rounded ends, and will not propagate like cracks. It is rather remarkable that the same problem persists in all welded parts with C quality level, because it yields the advantage of keeping the testing variables stable and facilitates the interpretation of the results obtained from mechanical testing.

8.1.2 Tensile Test Results

All steels used for the manufacturing of the specimens have been obtained from Erdemir company. This has provided us with the advantage of the full knowledge of the chemical and physical characteristics of the steels and the availability of fixed characteristics. The physical and chemical values of these steel sheets are shown on Erdemir Product Catalogue.

The tensile strength values of the materials used for tests, as shown on Erdemir catalogue, are 340-470 MPa, 410-560 MPa and 490-630 MPa for St 37, St 44 and St 52, respectively. As can be seen in Table 7.7, the tensile strength values for all the specimens, excluding the specimens no. 361 and 511 are consistent with the values shown on the catalogue. Since there are major deviations in the test results obtained, it is thought to be caused due to the slippage of the specimens in the tensile testing machine during the test. Therefore, the result of these tests must be omitted. Apart from these specimens, all results obtained are consistent with the catalogue values of all three steels for both the B quality level and C quality level.

According to Erdemir catalogue the yield stress values of the steels used are 225 MPa, 265 MPa and 345 MPa for St 37, St 44 and St 52, respectively. When Table 7.7 is examined, it can be observed that the upper yield and lower yield values of welded test specimens are higher than the catalogue values. This result is also an expected one, generally the steel manufacturers give the yield data of the steel smaller than the actual value to be in the safe-side in the market.

Elongation value has an important place among mechanical test results. Elongation values for St 37, St 44 and St 52 are shown as 24% (min.), 20% (min.) and 20% (min.), respectively, on Erdemir catalogue. The elongation values obtained from tensile tests are consistent with the catalogue values. There is no variation between the catalogue values and the results obtained from the specimens prepared in both quality groups for all materials. This demonstrates that the weld seam has satisfactory elongation values in both quality groups for all three materials. Furthermore, it also indicates that the gas porosity within the boundaries of C quality level does not have a negative impact on the elongation value of the weld seam.

All of the specimens have fractured from outside of the weld area. In this case, as expressed in known material theories and we can conclude that the weld seam has higher strength values than the base metal. The same results have been obtained in all steels and in both welding quality groups. This has been verified by the studies conducted for HAZ, as well.

When structural members are joined by fusion welding, the material of the plates has to be heated to its melting point and then cooled again rapidly under conditions of restraint imposed by the geometry of the joint. As a result of this very severe thermal cycle, the original microstructure and properties of the metal in a region close to the weld are changed. The volume of metal, or zone, is usually referred to as the Heat Affected Zone (HAZ).

The HAZ can be conveniently divided into a number of sub-zones and each sub-zone refers to a different type of micro structure and, perhaps more important, each structural type is likely to possess different mechanical properties. The structure type and its sub-zone width are partially determined by the thermal cycle, i.e. the complete cycle of the heating and cooling due to the movement of the arc and thermal properties of the base metal. In practice, most welds are multi-pass, and the weld metal as well as the unmelted parent metal, contains one or more HAZ and most of the scientific study on HAZ show that the yield and ultimate strength of the HAZ in steel are almost always higher than those of the parent material.

The results of tensile tests can be summed up as follows. As can be observed, all the fractures have occurred on the base metal. So, the porosity is not a very dangerous type of flaw under tensile loading. This is because round nature of pores which leads to lower stress concentration and lowers the possibility of crack initiation and crack propagation. In this study, the gas pores in the parts with C quality level have not negatively affected the results of tensile tests. All test results were expected from the tensile testing of welded parts. It must also be remembered that since the cracking occurs on the base metal, the results of tensile testing demonstrates that the welding seam have the required strength in both B and C quality levels. Therefore, the strength limits of the welded parts made from St 37, St 44 and St 52 steels are recognized as the strength limits of the base metal for the tensile testing, irrespective of whether the welding quality level is B or C.

8.1.3 Bending (Face) Test Results

As explained in the chapters regarding bending tests, bending tests are divided into two categories: bending face and root tests. The results of the bending face test will be discussed primarily in this chapter. The results obtained from this test are directly associated with the weld quality. The results of the test reveal that welded specimens with B quality level have successfully passed the bending test and have an elongation value between 8% and 10%. No cracking or fracture has been observed in the weld seam of specimens with B quality level. These results are the same for all three materials.

This case is totally different for the parts with C quality level. The test results reveal that cracks have not occurred in only two of the parts in group C with gas porosity (no.363 and 553) and that they have successfully passed the bending test. No cracks have occurred in specimen no. 363 and 553 and they had elongation values of 10% and 9%, respectively. However, cracks occurred on the weld seam of other part with C quality level. The F_m value read on the testing machine has fallen rapidly following the initiation of crack. These cracks have been small-sized and have not resulted in the fracture of the part, but have lowered the F_m value. The initiation of crack of course means that the part has failed in the test, however, while such small-sized cracks occur at high F_m values, the crack on the specimen no. 443 has occurred at a low F_m value and has propagated suddenly, leading to the fracture of the part. This may have caused from the fact that the porosity within the weld seam is too close to the tension surface.

Fig. 8.1: Bending Specimen with Crack Initiation

Fig. 8.2: Bending Specimen Fractured at Low F_m

As explained in Section 6, by using simple formulas, the bending test can be turned into a test whereby the mechanical features are determined under bending load, rather than being solely a control test. Here, all the flexural strength values of all parts have been found using equation (6.4). Of course, one cannot talk about a flexural strength for the parts with C quality level that have failed in the bending test, but it must be noted that the parts with C quality level have had a higher F_m and flexural strength values than the parts with B quality level until the initiation of cracks, which may be explained through the examination of Welding Procedure Specification (WPS). When the WPS given in the annex are examined, it can be observed that "back gauging" has been applied for attaining the weld seam with B quality. This procedure reduces potential root flaws, but has not been applied intentionally for C quality level and thus the formation of potential pores in the root has been allowed.

The researches in the literature demonstrate that the back gauging forms up a residual stress concentration on weld seam, which lowers the bending strength of the welded part. In a butt weld that is welded from both sides, if one side is welded out completely, followed by back gauging and complete welding of the second side, shrinkage of the second side weld will cause bending around the weld centerline. This explanation supports the case encountered in our study, which is, the parts with B quality level have lower F_m and flexural strength values although they have successfully passed the bending test without any flaw. This is true for only specimens made of St 37 and St 44, whereas it is not possible to make such a judgment for part made of St 52.

Considering the above comments and findings about the bending face test, it can be concluded that the existence of porosity in the weld leads to the initiation of cracking in case of bending load on the welded part. In this context, among all three types of steel, the parts with B quality level are more suitable for operation under bending load, compared with parts having C quality level. However, it has been observed that back gauging lowers F_m and flexural strength values in St 37 and St 44 steels due to high stress concentration. Therefore, high welding quality in St 37 and St 44 steels must be achieved without back gauging to the extent possible.

8.1.4 Bending (Root) Test Results

For bending root tests, which is the second category of bending tests, it would be beneficial to examine the specimens in terms of quality groups. The welded parts with B quality level have passed the bending test successfully in all types of steel. No crack has occurred in welded parts with B quality level in all three types of steel. Therefore, the comments for the bending face test may be repeated for the bending root tests. That is, in St 37, St 44 and St 52 steel types, the welded parts with B quality level can successfully withstand to the F_m load values identified in the result tables, under bending load.

In the C quality level, the results obtained from bending face and root tests are similar to each other. That is, cracking initiates and propagates during the bending tests on parts with porosity (with C quality level).

Another significant finding about root tests is that four of the parts with C quality level have successfully completed the bending test without any cracking. In this case, it would be beneficial to examine the flaws of the parts with C quality level (363, 553, 345, 355, 365 and 465) that have succeeded in face and root tests. When the depths of the flaws in specimens are reviewed on the basis of the ultrasonic test results, it has been observed that the gas pores in successful parts are deeper from the tension surface. It can be considered normal that no cracking occurs in this case, since the above-explained gas porosity structure is deeper from the tension surface, not leading to any cracking. These results are the same for all three types of steel.

The F_m and flexural strength values obtained from the welded parts with C quality level supports the explanations of bending face test with back gauging.

The bending root test has enabled us to make further comments about the parts with C quality level. Deeper location of flaws from the tension surface in parts that have successfully passed the bending test reveals that the location of porosity is also important besides its shape and size.

8.2 Conclusion

In the light of the above comments, the following assessments can be made. First of all, it can be said that the results estimated for tensile tests have been attained, whereas the results of bending tests have enabled us to make new comments. As a result of the observations during the thesis study and the interpretation of test results, the below listed-findings have been made:

i) Irrespective of whether their quality level is B or C, the tensile, yield and elongation values of parts manufactured from steel types St 37, St 44 and St 52 are limited to the tensile, yield and elongation values of the base metal. That is, the strength limit of the welded part is determined by the strength limit of the base metal. This applies for all three types of steel.

ii) With respect to its shape, porosity does not affect the initiation and propagation of cracks during tensile tests. This is confirmed also by the results of the test. While the results of the tensile tests vary from material to material, whether the welding quality level is B or C does not affect the result in the same type of material.

iii) Porosity in bending specimens is a serious problem. The parts to operate under bending load must be welded without causing any gas porosity, to the extent possible. B quality level is the most suitable weld quality level for parts to operate under bending load.

iv) Back gauging, which is used for increasing quality level and to minimize welding flaws in steel types St 37 and St 44 leads to increased stress concentration and lowers the F_m and flexural strength values of welded parts under bending load, which is expectable according to the results of the researches published in the literature. However, contrary to the generalizations made in the literature, this has not been observed in welded specimens manufactured from St 52 material.

v) In addition to its shape and size, the location of the porosity in the welding seam is also important. If the porosity is located far away from the tension surface, then such porosity affects less the initiation and propagation of cracks.

When evaluating all these results, it must be remembered that quality levels B and C have certain limits for flaws. However, in order to reduce variables during the thesis study, the welds without flaw have been used for the B quality level and porosity within the limits given in EN 25817 “Arc-Welded Joints in Steel – Guidance on Quality Levels for Imperfections” have been used for the C quality level. Therefore, the above mentioned results must not be generalized for B and C quality levels. General results may be obtained for B and C quality levels by conducting studies with more specimens and different flaw types in the future.

All these comments and inferences have been derived from limited amount of specimens. In order to be able to find out whether these results may be repeated and quantitatively finalize the results, the tests must be conducted with more number of specimens. This will enable the strengthening of the relation between the materials and the above comments.

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APPENDIX A

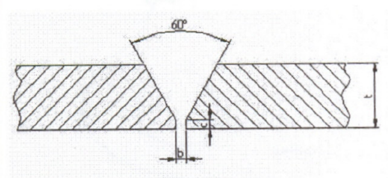
Table A.1: Welding Procedure Specification (WPS) for Quality Level B

Welding Procedure Specification(WPS) for Quality Level B

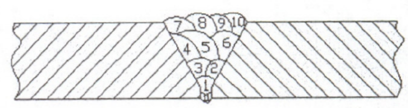
Manufacturer:	Sevinç Makine	**Date:**	01.10.2003
Constructer:	METU Mech. Eng. Dept Osman Alper Soylu	**Ref.**	EN 287-1 / EN 288-2
Welder's Name:	Hasan Gül		
Method of Preparation and Cleaning:	Machining, carefully grinding without over heating		
Welding Process:	111		
Joint Type:	BW		
Material Thickness:	20 mm		
Welding Position:	PA		
Material:	W01 - St 37		

WELD PREPARATION SKETCH

Joint Design



Welding Sequence



WELDING DETAILS

No.	Process	Filler Metal Diameter (mm)	Current [A]	Voltage [V]	Type of Current / Polarity	Wire Feed / Travel Speed [cm/min]	Heat Input [kJ/cm]
1	111	3,25	130	81,3	DC (+)	N/A	N/A
2	111	4,00	160	100	DC (+)	N/A	N/A
3	111	4,00	160	100	DC (+)	N/A	N/A
4	111	4,00	160	100	DC (+)	N/A	N/A
5	111	4,00	160	100	DC (+)	N/A	N/A
6	111	4,00	160	100	DC (+)	N/A	N/A
7	111	4,00	160	100	DC (+)	N/A	N/A
8	111	4,00	160	100	DC (+)	N/A	N/A
9	111	4,00	160	100	DC (+)	N/A	N/A
10	111	4,00	160	100	DC (+)	N/A	N/A
11	111	4,00	160	100	DC (+)	N/A	N/A

1 = Root Pass
2 - 6 = Filler Pass
6 - 10 = Capping Pass
11 = Back Gauging and Root Pass

APPENDIX A

Table A.2: Welding Procedure Specification (WPS) for Quality Level C

Welding Procedure Specification(WPS) for Quality Level C

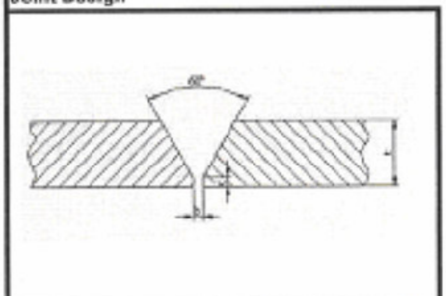
Manufacturer: Timsan Makine
Constructer: METU Mech. Eng. Dept
Osman Alper Soylu
Date: 01.03.2004
Ref. EN 287-1 / EN 288-2

Welder's Name: Erdem Ince
Method of Preparation and Cleaning: Machining, carefully grinding without over heating

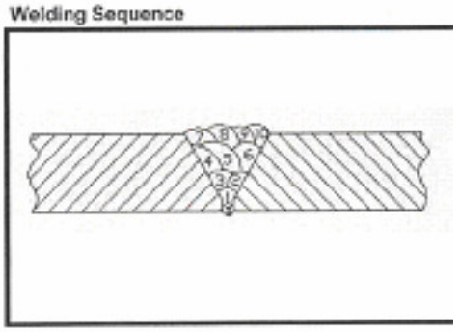
Welding Process: 111
Joint Type: BW
Material Thickness: 20 mm
Welding Position: PA
Material: W01 - St 37

WELD PREPARATION SKETCH

Joint Design



Welding Sequence



WELDING DETAILS

No.	Process	Filler Metal Diameter (mm)	Current [A]	Voltage [V]	Type of Current / Polarity	Wire Feed / Travel Speed [cm/min]	Heat Input [kJ/cm]
1	111	3,25	130	81,3	DC (+)	N/A	N/A
2	111	4,00	160	100	DC (+)	N/A	N/A
3	111	4,00	160	100	DC (+)	N/A	N/A
4	111	4,00	160	100	DC (+)	N/A	N/A
5	111	4,00	160	100	DC (+)	N/A	N/A
6	111	4,00	160	100	DC (+)	N/A	N/A
7	111	4,00	160	100	DC (+)	N/A	N/A
8	111	4,00	160	100	DC (+)	N/A	N/A
9	111	4,00	160	100	DC (+)	N/A	N/A
10	111	4,00	160	100	DC (+)	N/A	N/A
11	111	4,00	160	100	DC (+)	N/A	N/A

1 = Root Pass
2 - 6 = Filler Pass
6 - 10 = Capping Pass
11 = Root Pass