

DESIGN AND DEVELOPMENT OF WELDING ELECTRODE FOR STRUCTURAL STEEL

Thesis submitted in partial fulfillment of the requirements for the award of degree
of

MASTER OF ENGINEERING

in

Production & Industrial Engineering

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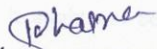
JUNE 2009

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Certificate

I hereby certify that the work which is being presented in the thesis entitled, "**Design and Development of Welding Electrode for Structured Steel**", in partial fulfillment of the requirements for the award of degree of Master of Engineering in Production & Industrial Engineering submitted in Department of Mechanical Engineering of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of *Dr. Rahul Chhibber* and refers other researcher's works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.



(Kuldeep Sharma)


This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.


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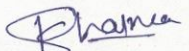
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ABSTRACT

This M.E. Dissertation aims to obtain fundamental knowledge about development of rutile electrodes for structural steel, of which information is scarce in international welding literature. In this work six rutile coated electrodes were prepared by increasing calcite (natural calcium carbonate — CaCO_3), at the expense of cellulose and Si-bearing components like Mica and China Clay, in the fluxes. This modification produced an increase in the slag basicity, which caused a marked increment in all-weld-metal toughness and modifications in operational behavior with a decrease in penetration and width of the weld bead, while maintaining the typical excellent operational characteristics of rutile electrodes. All-weld-metal hardness, tensile properties and Impact toughness were measured and metallographic studies were undertaken. the chemical Composition on analysis of the weld was also undertaken by making weld pads. Qualitative measurements of porosity, slag detachability, arc stability and smoke level (opacity) measurements were also carried out.

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Welding was invented around 100 years ago and, at least during the past 50 years, it has been the main fabrication method for structures made of steel and other metallic materials. There are several arc welding processes, which mean that there are many possible ways to carry out the welding operation.

With many of the methods, the mechanization of the process is possible and this can decrease the cost of welding. Due to the large number of consumables available, the flexibility required to achieve appropriate properties in the welded joint is very high.

1.1 WELDING



Fig 1.1 Welding Process
(Source: www.wikipedia.com) [3]

Welding is a fabrication process (shown in Fig. 1.1) that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the workpieces and adding a filler material to form a pool of molten material (the weld puddle) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the workpieces to form a bond between them, without melting the workpieces.

1.2 MANUAL METAL ARC WELDING

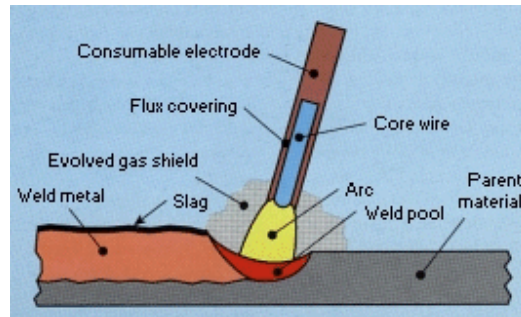


Fig 1.2 Manual Metal Arc Welding Process

(Source: Job Knowledge for Welders2, Connect, Nov 1994) [2]

Manual metal arc welding process (shown in fig. 1.2) was first invented in Russia in 1888. It involved a bare metal rod with no flux coating to give a protective gas shield. The development of coated electrodes did not occur until the early 1900s when the Kjellberg process was invented in Sweden and the Quasi-arc method was introduced in the UK.

It is worth noting that coated electrodes were slow to be adopted because of their high cost. However, it was inevitable that as the demand for sound welds grew, manual metal arc became synonymous with coated electrodes. When an arc is struck between the metal rod (electrode) and the workpiece, both the rod and workpiece surface melt to form a weld pool.

Simultaneous melting of the flux coating on the rod will form gas and slag which protects the weld pool from the surrounding atmosphere. The slag will solidify and cool and must be chipped off the weld bead once the weld run is complete (or before the next weld pass is deposited).

The process allows only short lengths of weld to be produced before a new electrode needs to be inserted in the holder. Weld penetration is low and the quality of the weld deposit is highly dependent on the skill of the welder.

1.3 SMAW OPERATION

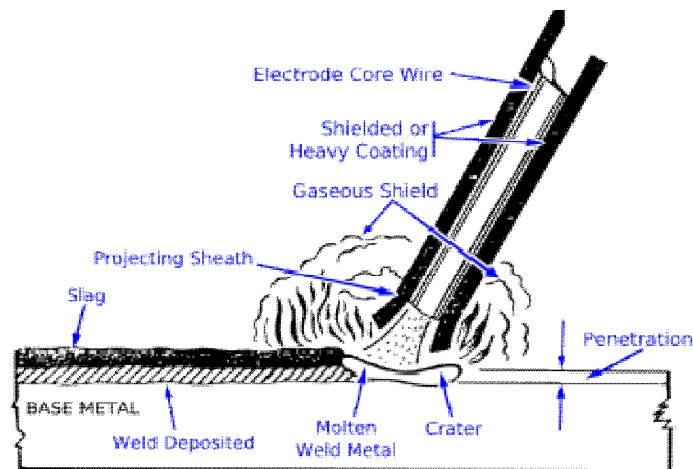


Fig 1.3 SMAW weld area
(Source: www.wikipedia.com) [3]

To strike the electric arc, the electrode is brought into contact with the workpiece in a short sweeping motion and then pulled away slightly. This initiates the arc and thus the melting of the workpiece and the consumable electrode, and causes droplets of the electrode to be passed from the electrode to the weld pool.

As the electrode melts, the flux covering disintegrates, giving off vapours that protect the weld area from oxygen and other atmospheric gases. In addition, the flux provides molten slag which covers the filler metal as it travels from the electrode to the weld pool. Once part of the weld pool, the slag floats to the surface and protects the weld from contamination as it solidifies.

Once hardened, it must be chipped away to reveal the finished weld. As welding progresses and the electrode melts, the welder must periodically stop welding to remove the remaining electrode stub and insert a new electrode into the electrode holder. This activity, combined with chipping away the slag, reduce the amount of time that the welder can spend laying the weld, making SMAW one of the least efficient welding processes. In general, the operator factor, or the percentage of operator's time spent laying weld, is approximately 25%.

The actual welding technique utilized depends on the electrode, the composition of the workpiece, and the position of the joint being welded. The choice of electrode and welding position also determine the welding speed. Flat welds require the least operator skill, and can be done with electrodes that melt quickly but solidify slowly.

This permits higher welding speeds. Sloped, vertical or upside-down welding requires more operator skill, and often necessitates the use of an electrode that solidifies quickly to prevent the molten metal from flowing out of the weld pool. However, this generally means that the electrode melts less quickly, thus increasing the time required to lay the weld.

1.4 ELECTRODE



Fig 1.4 Various welding electrodes and an electrode holder

(Source: www.wikipedia.com)

The choice of electrode for SMAW depends on a number of factors, including the weld material, welding position and the desired weld properties. The electrode is coated in a metal mixture called flux, which gives off gases as it decomposes to prevent weld contamination, introduces deoxidizers to purify the weld, causes weld-protecting slag to form, improves the arc stability, and provides alloying elements to improve the weld quality.

Electrodes can be divided into three groups—those designed to melt quickly are called "fast-fill" electrodes, those designed to solidify quickly are called "fast-freeze" electrodes, and intermediate electrodes go by the name "fill-freeze" or "fast-follow" electrodes. Fast-fill electrodes are designed to melt quickly so that the welding speed can be maximized, while fast-freeze

electrodes supply filler metal that solidifies quickly, making welding in a variety of positions possible by preventing the weld pool from shifting significantly before solidifying.

The composition of the electrode core is generally similar and sometimes identical to that of the base material. But even though a number of feasible options exist, a slight difference in alloy composition can strongly impact the properties of the resulting weld. This is especially true of alloy steels such as HSLA steels.

Likewise, electrodes of compositions similar to those of the base materials are often used for welding nonferrous materials like aluminum and copper. However, sometimes it is desirable to use electrodes with core materials significantly different from the base material. For example, stainless steel electrodes are sometimes used to weld two pieces of carbon steel, and are often utilized to weld stainless steel work pieces with carbon steel work pieces.

Electrode coatings can consist of a number of different compounds, including rutile, calcium fluoride, cellulose, and iron powder. Rutile electrodes, made of 25%–45% TiO_2 , are characterized by ease of use and good appearance of the resulting weld. However, they create welds with high hydrogen content, encouraging embrittlement and cracking.

Electrodes containing calcium fluoride (CaF_2), sometimes known as basic or low-hydrogen electrodes, are hygroscopic and must be stored in dry conditions. They produce strong welds, but with a coarse and convex-shaped joint surface.

Electrodes made of cellulose, especially when combined with rutile, provide deep weld penetration, but because of their high moisture content, special procedures must be used to prevent excessive risk of cracking. Finally, iron powder is a common coating additive, as it improves the productivity of the electrode, sometimes as much as doubling the yield.

To identify different electrodes, the American Welding Society established a system that assigns electrodes with a four- or five-digit number. Covered electrodes made of mild or low alloy steel carry the prefix E, followed by their number.

The first two or three digits of the number specify the tensile strength of the weld metal, in thousand pounds per square inch (ksi). The penultimate digit generally identifies the welding positions permissible with the electrode, typically using the values 1 (normally fast-freeze electrodes, implying all position welding) and 2 (normally fast-fill electrodes, implying horizontal welding only).

The welding current and type of electrode covering are specified by the last two digits together. When applicable, a suffix is used to denote the alloying element being contributed by the electrode.

Common electrodes include the E6010, a fast-freeze, all-position electrode with a minimum tensile strength of 60 ksi (410 MPa) which is operated using DCEP. Its cousin E6011 is similar except that it is used with alternating current. E7024 is a fast-fill electrode, used primarily to make flat or horizontal welds using AC, DCEN, or DCEP. Examples of fill-freeze electrodes are the E6012, E6013, and E7014, all of which provide a compromise between fast welding speeds and all-position welding.

1.5 STRUCTURAL STEEL

Structural steel is steel construction material, a profile, formed with a specific shape or cross section and certain standards of chemical composition and strength. Structural steel shape, size, composition, strength, storage, etc, is regulated in most industrialized countries.

1.5.1 Types of Structural Steel

The major types of structural steel are classified according to their chemical composition and processing characteristics

1. **Carbon or Carbon-Manganese Steels:** They are also referred to as mild structural steels. In addition to iron the primary chemical elements are carbon (C) and manganese (Mn). In the recent past steel known as high strength carbon steel was utilized to some extent. The higher strength was achieved by raising the carbon content but this had a negative effect on the weldability of the material
2. **High Strength Low Alloy (HSLA) Steels:** HSLA steels were developed over the past 30 years, making them currently the most used materials for steel framed structures. The

higher strength is achieved by lowering the carbon content and by adding certain alloying elements that provide for increased strength, ductility and toughness. All of these steels are weldable and some of them have increased corrosion resistance.

3. **High Strength Quenched and Tempered (QT) Alloy Steels:** They comprise a small group of materials with a specified minimum yield stress of 90 to 100 ksi, depending on the governing thickness of the delivered product. These are currently available only in the form of plates. The high strength is achieved through a combination of lower carbon content and a rapid cooling sequence that is quenching for the steel. This leaves the material with a very hard, fine grained martensitic structure. The ductility of the steel is significantly lower than that of the Carbon-Manganese or HSLA steel. Reheating or tempering improves the performance characteristics of the material especially the ductility.
4. **High Strength, Quenched and Self -Tempered (QST) Alloy Steels:** These steels are currently of limited availability. Their high strength is gained through selective quenching of certain regions of a shape but, in addition, the heat is stored in the material from the rolling procedure is utilized to provide the tempering effect. The localized quenching leave the product with distinctively different surface and interior regions, to the effect that the surface material tends to be much harder and more fine grained than that of the interior. Weldability appears to be good.

1.5.2 Chemical Composition

Iron (Fe): Iron is the single most important element in steel and comprises roughly 95% of the steel matrix. Materials with lower percentage of iron are not classified as “Structural”.

Carbon (C): Next to iron Carbon is the most important element in steel. Increasing the amount of carbon increases the strength and lowers the ductility. Current structural steels typically have carbon contents ranging from 0.05% to 0.25%. the lower amount of carbon also improves weldability.

Manganese (Mn): An important element, manganese have effect similar to those of carbon. It is used in structural steel in amounts varying from approximately 0.5 to 1.7%.

Chromium (Cr): chromium is primarily used to increase the corrosion resistance of steel. Structural steel has chromium contents ranging from 0.1 to 0.9%.

Copper (Cu): Copper is another primary corrosion resistance element used in steel. It is typically found in amounts not less than 0.02% in different types of structural steel.

Silicon (Si): Silicon is one of the two most important deoxidizers of steel meaning that it is very effective in removing oxygen from the steel during the pouring solidification process. Typical Si content of structural steel is less than approximately 0.4% but it must be at least 0.1% if the steel is to be considered fully killed.

Aluminium (Al): Aluminium is the other primary killing agent for structural steel. It is sometimes used in combination with silicon.

Columbium (Cb): Columbium is used to enhance the strength of the steel and is one of the key elements in the various HSLA grades. It has effects similar to those of manganese and vanadium and is often used in combination with vanadium. Due to weldability requirements Cb is used in amounts less than 0.05%.

Molybdenum (Mo): Molybdenum has effects similar to those of manganese and vanadium and is often used in combination with one or the other. This element especially increases the strength of the steel at elevated temperatures as well as the corrosion resistance. Mo content may be as high as 0.65%.

Nickel (Ni): Nickel is a powerful anti-corrosion agent and is also one of the most important elements to improve the fracture toughness of the steel. Ni contents generally vary between 0.25 and 1.5%, depending on the specifics of the steel.

Vanadium (V): Vanadium has effects similar to those of manganese, columbium and molybdenum. In particular, it aids in the development of tough, fine grained steel structure.

Sulphur (S) and Phosphorus (P): Both of these elements have detrimental effects on the strength but especially the ductility and weldability of the steel. Sulphur in particular promotes segregation in the steel matrix. For these reasons the contents of S and P are both restricted to no more than 0.04 to 0.05%.

1.5.3 Weldability of Structural Steel

For welding, it is imperative that the steel has a chemical composition that promotes the fusion

of the base metal and the weld electrode (filler) metal, without the formation of cracks and similar imperfections. This characteristic is referred to as weldability of the steel.

All currently available structural steel grades are generally weldable. For structural rehabilitation and/or retrofitting purposes, where the specifics of the steel that was used are not known, it is important for the designer and the fabricator to be able to assess whether the material is suitable for welding.

The most common measure of weldability is the Carbon Equivalent (CE), which is used to assess the combined effect of carbon and other chemical elements on the cracking susceptibility of the material. A material with a high carbon content is not weldable. The CE is also utilized to assess preheat requirements for a welded joint or assembly and take into account the influence of hydrogen and joint restraint.

1.6 DEVELOPMENTS IN STRUCTURAL STEEL

The large advance in terms of the weldability of structural steels came with the introduction of the thermo-mechanically (TM) processed steels at the beginning of the 1980s. Compared with the traditional normalised steels, the new steels had a much leaner composition, for the same yield strength. The carbon content in particular was reduced and the strength was obtained from finer grain size and increased dislocation density. Sometimes, accelerated cooling was used, adding extra strength as the steel transformed to bainite rather than ferrite.

In addition to the lower carbon content, the quality of the steels was improved significantly by a reduction in the impurity element (sulphur and phosphorus) content. It is difficult to envisage a similar major development in steels in the near future. Slow and continuous improvements will probably be made to TM steels in terms of their impact properties, for example they may find new applications, as there will probably be no major changes. There will be no need to make any significant changes to the consumables used for welding these steels.

In the new European standard EN 10 113-3, TM steels with yield strengths of up to 460 MPa are specified. TM steels can now be produced at many steelworks. What might differ between suppliers is the combination of plate thickness and yield strength that can be delivered. Many of the steels supplied with yield strengths of up to approximately 500 MPa are made using the TM process. For the highest strength levels in this range, the production process is determined by the

plate thickness. For thinner plates, the TM process can be used, but for heavier plates it is necessary to use quenching and tempering to obtain the properties. Above approximately 500 MPa, all steels are of the QT type. These steels are also of high quality, with low impurity content and good weldability. However, with increasing strength levels and increased thickness, more alloying is needed, making preheating necessary.

A trend that has continued for some years involves using steels of higher strength. The advantage of this is obvious; structures can be made with thinner plates, reducing the weight and thereby improving the opportunity for higher loads. It should be noted that there are situations in which a structure cannot take advantage of thinner plates, such as when buckling, stiffness or fatigue strength is the design criterion.

High-strength steels are commonly defined as steels with yield strength of more than 350 MPa. These steels now have found their way into many areas of construction. In several new spectacular bridge constructions, TM steels with yield strengths of 420 or 460 MPa have been used. One example is the Great Belt Bridge in Denmark which was built during the mid-1990s and recently went into operation. Part of the bridge is made in the form of a steel suspension bridge, using some 80,000 tonnes of steel. Half this amount is accounted for by TM steels, with yield strength of 420 MPa.

Another example from the bridge sector, in which a very high-strength QT steel is used, is the world's largest suspension bridge, the 1,990 m long Akashi bridge in Japan. The construction of this bridge was completed in 1997 and the bridge is now in operation. In the box girders of this bridge (comprising hundreds of tonnes of the steel), a very high strength steel, HT780, with a yield strength of more than 780 MPa was used. It is particularly interesting to note that this steel only needed less than 50°C of preheating, despite its high strength, due to the elaborate alloying technique, combined with the quenching and tempering technique.

Examples of applications for high-strength steels with yield strengths of up to around 500 MPa include standard structural steel works, excavator equipment, pipelines, cranes, roof support in mines and, of course, offshore constructions.

Steels of higher strength such as 690 MPa are used for trailers for heavy haulage work, cranes with a high lifting capacity, dumper bodies and so on. For steels with even higher strength (900 MPa and above), typical applications include penstocks, conveyor systems and mobile bridges.

For steels with yield strength of 350-450 MPa, there are usually very few welding problems. The problems that can arise here include low toughness in the weld metals, often associated with increased nitrogen content, due to the use of too long an arc. If low- hydrogen consumables are used, hydrogen cracking is very rarely a problem. If it arises, it is related to the welding of heavy plates. Solidification cracking may occur in very special circumstances, but it should generally pose no problems. Impact toughness in high- dilution welds, such as one-sided welding with only one bead, can sometimes be low. This is, however, often due to some incompatibility between the base metal and the consumable.

It is not until steels with yield strength of 600 MPa or above are used that welding may become somewhat problematic and require more caution. The steels are used in demanding applications, requiring good toughness at low temperatures in many cases. In this case, two problems may occur. The first involves finding a weld metal with a yield strength higher than that of the steel and at the same time possessing good impact toughness. There are an increasing number of consumables with these properties, but there may still be problems when it comes to combining high productivity and good mechanical properties. This is discussed in more detail in the paper by L-E Svensson [4].

The second problem is related to hydrogen cracking. With the steel developments that have taken place, including a lean alloying content, the weldability of the steels has been increased. In particular, the need for preheating has been reduced dramatically. This is especially true of steels of lower strength, such as 350-500 MPa steels. For these steels, the welds metals are also lean in alloying content and do not require preheating. However, when it comes to the high-strength steels, the situation is more complicated. The only way to increase the strength of these weld metals is to increase alloying. The advanced processing routes used for the steels can naturally not be applied to the weld metal. So, in a situation in which there is less harden ability in the HAZ than in the weld metal, there may be several reasons why hydrogen cracking would be more likely to occur in the weld metal. Preheating must then be prescribed to protect the weld metal rather than the HAZ of the parent plate. This is a somewhat new situation and, although fabricators have learnt how to handle it, there is a lack of fundamental knowledge about weld metal hydrogen cracking which must be remedied.

One solution that might appear to an attractive means of resolving this situation is a further

reduction in hydrogen content from the consumables. Developments in which the hydrogen content of the weld metals has been reduced have already been in progress for many years.

There are several reasons for believing that the rate at which this downward trend will continue will be slower in the future than it has been in the past. It will be increasingly difficult to make further reductions from the very low levels that have already been achieved. The hydrogen content can be reduced by a number of measures. Unfortunately, these changes often tend to have a negative effect on other properties, such as welding characteristics. So, a further reduction in hydrogen will lead to consumables which are less attractive to the welder. Apart from hydrogen stemming from the consumable, there are other sources of hydrogen, such as the surrounding atmosphere, the base material or dirt and oil on the plate and joint surfaces.

So, the amount of hydrogen in the weld pool can differ from the hydrogen content specified by the electrode manufacturer. Naturally, the hydrogen content of the consumable is also affected by the possible moisture absorption. Although low moisture absorption electrodes have been developed, some absorption always takes place.

To benefit fully from the development of steels, to increase productivity during welding, systematic investigations need to be made, partly to be able better to define the preheating necessary for safe welding, but also in order possibly to develop the weld metals still further with the aim of making them crack-resistant while maintaining the mechanical properties.

CHAPTER 2

REVIEW OF LITERATURE

While undergoing review of literature available it was found that few people have work towards development of welding consumables for high-strength steels using various welding

processes. It was observed that the papers dealing with development of welding electrodes for high strength steels using SMAW are particularly less.

K. Sampath [5]

in this paper an innovative constraint based modeling approach was used to successfully specify the chemical composition range for advanced consumable electrodes intended for gas metal arc welding (GMAW) of high-strength steels for critical U.S. Navy applications.

Initially, various U.S. Navy requirements for advanced consumable electrodes were converted into a set of constraints that related chemical composition of steels to certain metallurgical characteristics with appropriate numerical ranges.

The metallurgical characteristics and their numerical ranges, in turn, were used to identify critical elements for compositional control, and to specify the compositional ranges for the individual alloy elements.

Vincent Van Der Mee, Fred Neessen & Lincoln Smitweld [6]

Application of high strength steels may offer many advantages. Today, high strength steels are increasingly applied in pipelines, cranes, offshore construction, bridges, minesweepers, etc.

In order to meet market requirements for a wider range of steel grades, consumables for applicable processes need to be available, whether it is for manual or mechanized welding. In this paper, an overview is given of criteria and results in the development process of FCAW, SMAW, GMAW and SAW consumables for steel grades up to S690.

Initially, weldability is the feature to be met. Next, chemical composition and mechanical properties in the as welded and/or post weld heat treated condition need to be demonstrated, followed by a consumable classification according to AWS, EN or other. Influence of individual elements (like Mn, Ni, Mo, Ti or B) on weld metal toughness and strength level is discussed.

M.B. Henderson, D. Arrellb, M. Heobel, R. Larssonb and G. Marchantc [7]

The continued drive for increased efficiency, performance and reduced costs for industrial gas turbine engines demands extended use of high strength-high temperature capability materials, such as nickel based super alloys.

To satisfy the requirements of the component design and manufacturing engineers these materials must be capable of being welded in a satisfactory manner. The paper describes the characteristic defects found as a result of welding the more difficult, highly alloyed materials and reviews a number of welding processes used in the manufacture and repair of nickel alloy components. A number of factors are found to affect the propensity for defects: composition (aluminium and titanium content), grain size, pre and post-weld heat treatment, as well as the welding process itself (control of heat input and traverse speed).

E.Bauné, C.Chovet, B.Leduey, C.Bonnet [8]

The use of (very) high strength steels for the design of high performance steel structures is highly promising as they can allow for substantial savings due to the thickness reduction of structural parts. The application of these steels for structural design, however, is not yet fully developed as limitations are imposed by design codes currently in effect. In addition, when welding is involved during fabrication, deterioration of the properties of these materials may occur.

As an example, welding of high strength steels can induce a loss in toughness both in the material heat affected zone and in the weld metal, depending on the welding process, the welding consumable and the welding procedure, with respect to the base material chemical composition.

Also, when a post weld heat treatment (PWHT) needs to be applied for certain applications, a change in the weldment properties takes place, what may appear as another limiting factor. For these reasons recommendations on the welding of high strength steel structures are needed for the steel and welding communities, as well as for fabricators.

This paper provides several examples of mechanical properties obtained on various welded joints performed on high strength steels over 690MPa. The paper outlines the strategy followed to develop submerged arc welding (SAW) and shielded metal arc welding (SMAW) consumables dedicated to the welding of these steels.

All-weld-metal characterization results are provided, together with results obtained on joints carried out on the base material, both in the as-welded condition and after a PWHT, this latter often being unavoidable in the fabrication of pressure vessels.

The influence of the base metal dilution and the welding procedure upon toughness and tensile properties is discussed, while an overmatched weld metal is looked for. Secondly, various welding solutions have been developed for steels ranging from 690 through 1100MPa within the Air Liquide Welding group.

Ashish Kapoor and Jonathan Ogborn [9]

Strain based design of pipelines for seismic environments using high strength materials is a relatively recent approach in the world of line-pipe installation. The development of suitable welding consumables for these applications has also been lagging.

This paper outlines the efforts of a consumable manufacturer to fill that gap and design SMAW consumables for strain based applications. The main challenge in this exercise lies in achieving a high enough strength level while at the same time maintaining adequate toughness levels.

A microstructure-optimization approach was followed in the design process to achieve the optimum combination of properties. Since the balance of strength and toughness is pivotal to the application, the welding procedure becomes a critical component of the design process.

This paper highlights the importance of maintaining a tight control on the welding process in order to achieve consistently acceptable mechanical properties. Due to the high strength levels involved, a low hydrogen system was used as the design basis.

Testing was done with both an uphill and downhill welding electrode slag system. Since the choice between these two types of low hydrogen SMAW electrodes is largely a matter of contractor preference and/or a function of the availability of skilled welders, it was considered important to have a choice of both types of strain-based electrodes.

S. S. Babu, J. M. Vitek [10]

Welding consumables are used to join a wide range of materials from steels to advanced nickel base superalloys and, therefore, play a critically important role in the welding industry. The ability to optimize welding consumables in a reliable and efficient manner is crucial to ensure that the US welding industry remains competitive in a global marketplace.

Welding consumables must be designed to provide the required operational characteristics (such as arc stability over a wide range of parameters, deposition rate appropriate to the application, minimal spatter and fume, etc.) and weldment properties (such as cracking

resistance, strength, toughness, etc.). The operational characteristics and weldment properties are not independent of each other. Moreover, the nature of the interdependency of these two characteristics is a function of the type of material being joined and the welding arc atmosphere.

Traditional welding consumable design involves expensive and time-intensive experimental trials, characterization and optimization based on trial and error. In this research, we propose to develop an alternative and novel welding design and optimization methodology that should result in greater efficiency and improved performance.

This alternative methodology will rely on fundamental laws of physical processes that determine the operational characteristics and weldment properties. Some of these physical processes include arc-plasma interactions, gas-metal reactions, slag-metal reactions, solidification and solid-state phase transformation. Over the past three decades, significant progress has been made in the fundamental understanding of individual physical process.

Many theoretical and computational models have been developed to describe individual process as well as some of the complex interaction. However, there is nearly a total absence of applied research to extend this knowledge to the design and optimization of welding consumables.

Recent collaborative research between ORNL and Lincoln Electric Company has shown the potential of such applied research by successfully understanding microstructure development in self-shielded flux cored arc welds. This was made possible by coupling the laws of gas-metal reactions, thermodynamic phase stability, and atomic diffusion models of phase transformations.

David W. Gandy, Shane J. Findlan, R. Viswanathan [11]

As the U.S. fleet of fossil power plants age, utilities are forced to perform more and more repairs on such components as turbine casings, main and reheat piping, headers, and other components that have experienced high-temperature degradation.

This paper presents information from two surveys on the weld repair technologies currently used by utilities and repair organizations to extend the life of high-temperature, high-pressure components. The initial survey included responses from 28 EPRI member utilities on various repair issues ranging from condition assessment to preheat/post weld heat treat to filler metals

employed. The second survey was forwarded to repair vendors and OEMs to gain their perspective on utility industry repairs.

S. F. Kane, A. L. Farland, T. A. Siewert AND C. N. McCowan [12]

This paper summarizes the development and qualification of an appropriate welding consumable for a demanding cryogenic magnet application. It begins with a review of the research conducted on cryogenic fracture toughness of wrought and welded austenitic stainless steels.

This research shows that certain elements of the composition have a powerful effect upon the steel's fracture toughness at 4 K. In particular, the higher oxygen content in the weld manifests itself as inclusions, which have a severe detrimental effect upon the fracture toughness. This one factor accounts for most of the difference in toughness between wrought and weld materials of similar composition, and is a function of the weld process.

Also, welds enriched with manganese and nickel has demonstrated improved fracture toughness. These discoveries were combined in the development of a nitrogen- and manganese-modified, high-nickel stainless-steel alloy.

It produced gas metal arc welds with superior cryogenic mechanical properties (yield strength near 900 MPa at 4 K and a Charpy V-notch impact energy near 140 J at 76 K) when the procedures were modified to reduce the oxygen content.

Hiroshige Inoue, Ryo Matsushashi, Yutaka Tadokoro, Shigeo Fukumoto, Takeshi Hashimoto, Manabu Mizumoto, Hajime Nagasaki [13]

A highly corrosion-resistant stainless steel, NSSC260A, for application to chemical cargo tankers and welding consumables for the steel were developed.

The stainless steel and welding consumables were designed to exhibit good resistance to corrosion by sulfuric acid, crude phosphoric acid and salt water. The developed welding consumables, flux-cored wire NITTETSU FC-317LNCU for CO₂ welding and NITTETSU BF-317LNCU (flux)NITTETSU Y-316C (solid wire) for submerged arc welding, proved that it is

possible to attain weld joints that satisfy required corrosion resistance and mechanical properties, and their actual use for construction of chemical cargo tankers began in June 2004

T Zacharia, J M Vitek, J A Goldak, T A DebRoy, M Rappazl and H K D H Bhadeshia [14]

Recent advances in the mathematical modeling of fundamental phenomena in welds are summarized. State of the art mathematical models, advances in computational techniques, emerging high-performance computers, and experimental validation techniques have provided significant insight into the fundamental factors that control the development of the weldment. The current status and scientific issues in the areas of heat and fluid flow in welds, heat source metal interaction, solidification microstructure, and phase transformations are assessed. Future research areas of major importance for understanding the fundamental phenomena in weld behaviour are identified.

David Gandy, Richard Smith, Ming Lau [15]

ASME B&PV Code currently allows weld repairs of carbon and low alloy steel components without high temperature post weld heat treatment provided that temper bead welding techniques are rigidly enforced. Repairs using the SMAW process may be performed using the “half-bead” welding method or the “butter-bead” technique.

A half-bead method have proven difficult to control due to inaccuracies in grinding between first and second layer passes and often leads to increased radiological exposure. This study examines temper bead welding using the SMAW process without using grinding between passes from both a metallurgical and mechanical standpoint.

Furthermore, the results of several industry testing programs aimed at controlling the SMAW process to yield high toughness base metal HAZ while minimizing potential for cold high-restraint cracking and/or hydrogen delayed cracking are discussed.

Jiri Sopousek, Rudolf Foret, Vit Jan [16]

Results of computer simulations of long-term service exposure for weldments of the CSN 15 128 / P91 and SK3STC / P91 steels are presented and compared with corresponding results of phase and composition experiments. The welded material P91 (EU standard: X10CrMoVNb 9-1) represents progressive chromium steel alloyed with Mo, V, C, and N. The

CSN 15 128 (EU standard: X10CrMoVNb 9-1) material is low-alloy Cr-Mo-V steel. The SK3STC alloy (EU standard: 12CrMo 10-10) represents the consumable electrode material. The stability of the weldment microstructure is investigated at elevated temperatures (500-700°C). The simulation method is based on the CALPHAD approach complemented with the theory of multi-component bulk diffusion, local condition of phase equilibrium and the assumption that diffusion is the process that controls the rate of phase transformation (the DICTRA software is used).

Significant phase profiles, concentration profiles, and phase transformation processes in diffusion-affected zone are simulated, investigated, and compared with experimental results. The potential risky carbon depleted region inside each weld joint is discussed. The method described can be used to predict microstructure instability in weld joints.

U. Mitra, C.S.Chai and T.W.Eagar [17]

During submerged arc welding, as in other flux shielded welding processes, chemical reactions takes place between the molten flux and the metal. This reaction between the slag and the metal results in compositional changes affecting the structure and the properties of the weldment. Thus, in order to control the mechanical properties of the weldment and match them with those of the workpiece, it is necessary to estimate the extent of interaction between the metal and the slag.

This need is more acute now since major improvements in steel making technology have improved base metal properties and have resulted in the creation of entirely new classes of steel, such as High Strength Low alloy (HSLA) steels for use in ship building, pipelines, pressure vessels etc. thus far, there is no general method for determining weld metal composition.

U. Mitra and T.W.Eagar [18]

A kinetic model is developed to describe the transfer of alloying elements between the slag and the metal during flux shielded welding. The model accounts for change in alloy recovery based on the geometry of resulting weld bead.

It also distinguishes compositional differences between single pass and multiple pass weld beads. It is further shown that the final weld metal oxygen content is directly related to the weld solidification time as well as the type of flux used.

N.T.Jenkins, P.F.Mendez, T.W.Eagar [19]

Welding fume composition is dependent on the temperature at the surface of a GMAW electrode. This temperature varies with welding parameters and affects the amount, composition and type of fume.

A thermodynamic analysis based on the superheating expected at the surface of the molten electrode tip is presented to help understand observed fume composition.

CHAPTER 3

FORMULATION OF PROBLEM

Structural

steel is preferred materials for structural engineering as well as manufacturing of pipelines tanks etc. The welding electrodes for these steels are commercially available but the coating compositions are patented and are not widely reported in literature.

In the present work electrode coating was designed and formulated with the help of the available literature.

The desired qualitative characteristics during welding such as less porosity, less smoke, good arc stability and slag detachability would be ascertained to develop a quality coated electrode for welding of structural steel. In addition weld bead characteristics would also be ascertained to assess the quality of weld made using these coated electrodes.

Necessary quantities of alloying elements was added in form of Ferro-alloys and pure metal powders to get the desired chemistry of the weld bead

The mechanical testing and micro structural configuration of the weld metal was carried out to determine, and co-relate the properties of weld metal with micro structural variations, under the influence of different coating compositions and welding parameters.

The variations in calcite percentage in the flux composition were made and the weld bead results, resulting weld metal properties were analysed.

4.1 EXPERIMENTAL FLUX FORMULATION

During the course of this investigation, a series of experimental electrodes with different flux formulations was produced. The experimental electrodes were produced in small batches (100g flux each) in the welding laboratory.

The coating contains the following major compounds:

- Rutile (TiO_2)
- Fluorspar (CaF_2)
- Calcite (CaCO_3) and dolomite ($\text{CaCO}_3\text{MgCO}_3$)
- Iron powder
- Slag formers, binders, extrusion aids and deoxidizers



Fig 4.1 Major Compounds of Coating

4.2 COMMON COATING INGREDIENTS AND THEIR FUNCTIONS

- Fluxing agents: Silica, CaO, and Fluorspar.
- Slag formers: Rutile, Titania, potassium titanate, Asbestos, Alumina, Silica flour, iron oxide, Fluorspar etc.
- Arc stabilizers: potassium, Silicate, potassium oxalate, Zirconium carbonate, Lithium carbonate, Titania etc.
- Gas forming material: Cellulose, Wood Floor, Lime Stone.
- Slipping agents (for easy extrusion): Glycerine, China Clay, Talc, Mica etc.
- Binding agent: Sodium Silicate, Dextrin, potassium Silicate, Sugar.
- Deoxidizers and alloying elements: Ferrosilicon, Ferro-chromium, Ferromanganese, electro-nickel, Electro manganese etc.

4.3 BASICITY INDEX

The BI as adopted by International Institute of Welding is given in terms of the weight percentage of various oxides and fluorides constitutes.

$$\text{BI} = \frac{\text{CaF}_2 + \text{CaO} + \text{R}_2\text{O} + 0.5(\text{MnO} + \text{FeO})}{\text{SiO}_2 + 0.5(\text{Al}_2\text{O}_3 + \text{TiO}_2 + \text{ZrO}_2)}$$

Where RO represents alkaline earth oxides and R₂O the alkali oxides. However T.W.Eagar [18] has considered CaF₂ has a neutral component in the slag and omitted CaF₂ from the above formula for his calculation purposes.

The flux is termed acidic or basic depending on the value of BI. One of the major differences between basic and acidic fluxes is their ability to rid the molten metal of residual sulphur and phosphorus.

There are four levels of BI for standardisation of flux give as follow:

- Fluxes having basicity index less than 1 are incapable of controlling the sulphur content of the weld metal effectively. In short BI <1=Acidic.
- Fluxes having basicity index (BI) between 1 and 1.5 are capable of controlling the sulphur effectively but not oxygen in the weld metal. In short 1 < BI < 1.5=Neutral.

- Fluxes having basicity index (BI) between 1.5 and 2.5 are capable of controlling the Sulphur and oxygen content effectively and lowering the transition temperature by controlling Si content in the weld metal to a certain extent. In short $1.5 < BI < 2.5 = \text{Basic}$.
- Fluxes having basicity index (BI) above 2.5 are capable of lowering the Charpy V notch transition temperature down to -40°C or even below by controlling the composition and microstructure of weld metal suitably. In short $BI > 2.5 = \text{High Basic}$.

4.4 MANUAL ELECTRODE PRODUCTION

The raw materials were weighed and were mixed for approximately 7 minutes to obtain a homogeneous dry flux mixture. A liquid silicate binder was then added to the dry flux mixture, followed by mixing for further 10 minutes. The binder consists of a complex mixture of different alkali silicates with a wide range of viscosities. The flux was then extruded onto a 3.15 mm diameter mild steel core wire and coating diameter of 5 mm, coating factor of 1.58, where the coating factor represents the ratio of the core wire diameter to the final electrode diameter. Core wire from the same cast was used for all the experimental electrodes.

After manual extrusion of the electrodes were baked. The baking cycle consisted of 30-40 minutes at 120°C .

These electrodes were tested by taking weld bead on plates and finally 6 types of flux coating composition were obtained by varying the calcite (natural calcium carbonate- CaCO_3) from 7.5 to 20 wt% at the expense of cellulose, ferromanganese, fluorspar and Si-bearing raw materials (quartz, kaolin, mica, and feldspar) in the dry mix.

4.5 ELECTRODE EXTRUSION FOR EXPERIMENTATION



Fig 4.2 Extrusion Machine

The final six electrodes were finally extruded from SK Electrode Manufacturers Bathinda. All the electrodes were produced with the same quantity of potassium silicate and the same wire and powder raw material batches. The coating dry mix composition and the slag chemical analyses, with the corresponding basicity indexes (BI) calculated according to Boniszewski (Ref. 28) are shown in Table 4.1.

Table 4.1: Coating Composition (wt %)

Coating	7.5%	10%	12.5%	15%	17.5%	20%
Dry Mix Constituents	Calcite	Calcite	Calcite	Calcite	Calcite	Calcite
TiO₂	45	45	45	45	45	45
Aluminite	5	5	5	5	5	5
CaCO₃MgCO₃	7.5	7.5	7.5	7.5	7.5	7.5
Cellulose	5	2.5	0	2.5	0	0
Ferromanganese	10	7.5	7.5	5	7.5	7.5
CaF₂	2.5	5	5	2.5	2.5	5
China clay	7.5	10	7.5	7.5	5	0
Mica	5	2.5	5	5	5	5
Tel com powder	2.5	2.5	2.5	2.5	2.5	2.5
Iron powder	2.5	2.5	2.5	2.5	2.5	2.5
Basicity Index	0.53	0.66	0.73	0.78	0.85	0.94

In all tables and/or figures, the electrodes will be identified as 7.5% Calcite, 10% Calcite, 12.5% Calcite, 15% Calcite, 17.5% Calcite or 20% Calcite, depending on the percentage of calcite in the electrode coating (Table 4.1).

4.6 EXPERIMENTAL SPECIMEN FORMATION

4.6.1 Operational Properties: Manual Welding

The operational behavior of the six electrodes was studied using an AC-DC 350-A power supply set to AC, alternating current; DC(+), direct current, positive pole to the electrode; and DC(-), direct current, negative pole to the electrode; in flat (F), position.

Table 4.2 Welding Parameters for the Test Specimen

Parameters	7.5% Calcite	10% Calcite	12.5% Calcite	15% Calcite	17.5% Calcite	20% Calcite
Current (A)	145	145	145	145	145	145
Voltage (V)	25	25	25	25	25	25
Welding Speed (mm/s)	3.7	3.6	3.3	3.1	2.9	2.7
Heat Input (KJ/mm)	1.1	1.1	1.2	1.2	1.3	1.4

4.6.2 Weld Bead on Plate Testing

The weld beads with various composition of calcite coating were laid on the test palates (70mm×40mm×5mm). The power supply was varied as described in 4.6.1. After completion of all welds on plates, the weld bead geometry measurements were taken.

4.6.3 Preparation of Weld Coupon For All Weld Metal Testing

The plates of dimension 480mmx150mmx12mm were machined on Shaper and V groove angle of 60° and root face of depth 2mm was cut using shaper. These plates were then cleaned with acetone and then welded using the electrodes developed by varying calcite compositions.

The following figure shows weld groove geometry in mm which is to be cut in plate for the preparation of weld coupon.

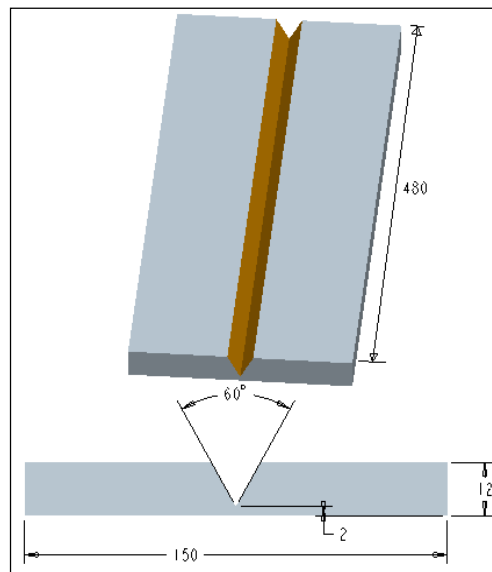


Figure 4.3: Weld Groove Geometry

(All dimensions in mm)

4.6.4 Chemical Composition

Weld metal chemical composition were obtained from both the transversal cut samples extracted from the all-weld-metal coupons and from the weld pads, using atomic absorption spectrometer.



Figure 4.4: Atomic Absorption Spectrometer

4.7 Mechanical Testing

4.7.1 Micro Hardness Testing

Micro-indentation hardness testing (or micro hardness testing) is a method for measuring the hardness of a material on a microscopic scale. A precision diamond indenter is impressed into the material at loads from a few grams to 1 kilogram. The impression length, measured microscopically, and the test load are used to calculate a hardness value. The hardness values obtained are useful indicators of a material's properties and expected service behaviour. Conversions from micro-indentation hardness values to tensile strength and other hardness scales (e.g., Rockwell) are available for many metals and alloys.

The indentations are typically made using either a square-based pyramid indenter (Vickers hardness scale) or an elongated, rhombohedral-shaped indenter (Knoop hardness scale). The tester applies the selected test load using dead weights. The length of the hardness impressions are precisely measured with a light microscope using either a filler eyepiece or a video image

and computer software. A hardness number is then calculated using the test load, the impression length, and a shape factor for the indenter type used for the test.



Fig. 4.5 Micro Hardness Tester

In the present work micro hardness measurements were covered out in all weld regions of the test specimens of size 10mmx10mmx55mm, cut from the weld coupon. These specimen were polished and mounted on micro hardness tester,250 gm load was applied and reading were taken.

4.7.2 Micro Structural Testing

The specimen is examined in the as-polished condition in the weld metal regions. Mild steel specimen and weld samples were polished then etched with 2% nital before testing

The metallographic study was carried out on transverse cross sections of the all weld- metal test assemblies.

4.7.3 Impact Testing

The Charpy test measures the energy absorbed by a standard notched specimen while breaking under an impact load. The standard Charpy Test specimen of size of 55mm×10mm×10mm having a V notch machined across one of the larger dimensions.



Fig 4.6 Impact Testing Machine

The V-notch: 2mm deep, with 45° angle and 0.25mm radius along the base was used. By applying the Charpy Test to identical specimens at different temperatures, and then plotting the impact energy as a function of temperature, the ductile-brittle transition becomes apparent.

Impact testing was determined on the transverse cross section of the all-weld metal test assemblies at the Charpy V notch location (Fig. 4.7) using the Vickers 1000-g scale. From each all-weld-metal test assembly, a Minitrac test specimen was extracted.

The steel for these was in the form of plates of 10mm in thickness which had been cut out of the center for the formation of the notch. Charpy samples were cut in a transverse direction to the weld beads.

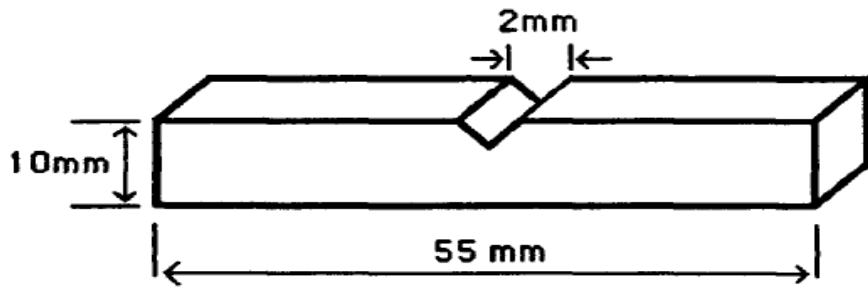


Fig 4.7 Weldment Dimensions

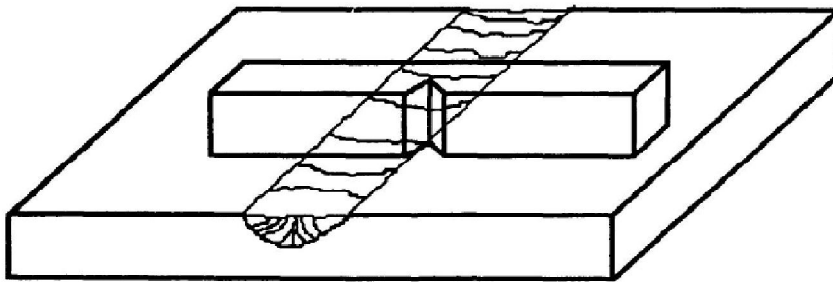


Fig 4.8 Charpy Weldment Specimen

The given figure shows the Charpy specimen which was cut from all weld metal.



Fig 4.9 Charpy Specimen

4.7.4 Tensile Testing



Fig 4.10 Cutting V Groove on Plate for Tensile Specimen Formation

Tensile test is carried out by gripping the end of the specimen in a tensile testing machine and applying and increasing pull on to the specimen till it fractures.

During the test, the tensile load as well as the elongation of a previously marked gauge length in the specimen is measured with the help of load dial of the machine and extensometer respectively. These readings help plotting stress strain curve. After fracture, the two pieces of the broken specimen are placed as if fixed together and the distance between two gauge marks and the area at the place of fracture are noted.

V groove on two plates were cut as shown in figure 4.10 and after doing welding in V groove of 2 plates by six electrodes then tensile weldment specimen is to be cut from these plates for tensile testing.

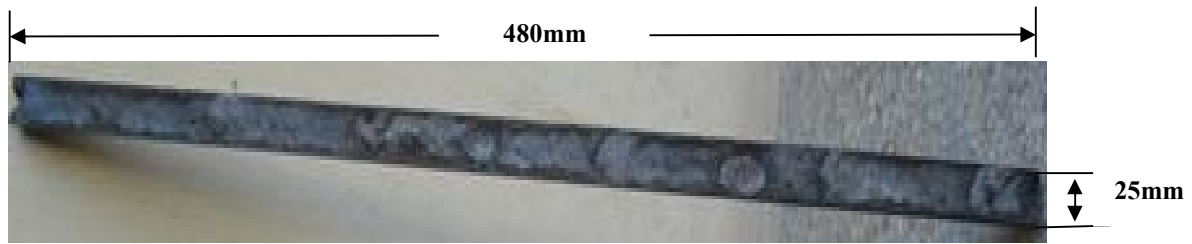


Fig 4.11 Tensile Weldment Specimen

4.7.5 Weld Bead Geometry



Fig 4.12 Weld Bead Specimen

The weld beads obtained from the entire six electrodes were utilized to measure bead geometry. The transverse cut samples obtained from the weldments were etched with 5% Nital for 5s to examine the bead geometry. The vernier caliper gauge mentioned previously was employed to measure bead width (BW), penetration (P), and weld reinforcement (WR) of the bead.

4.8 Smoke Testing

Smoke test was done to measure the smoke levels that were generated while welding on the specimen, which is hazardous to health. CaF_2 was added in six electrodes in different quantities to measure the smoke levels.



Fig 4.13 Smoke Testing of Welding Electrode by Smoke Meter

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 SLAG CHARACTERISTICS

As expected, all the flux was of the rutile type but with slight variations. They all completely covered the beads and, once removed, the bead borders remained clean. In the flat position, 7.5%, 10% and 12.5% calcite slag did not interfere with the weld pool; the bead was well shaped and deposited quickly. On the other hand, 17.5% and 20% calcite slag was too abundant and tended to interfere with the weld pool. In the last case, the weld was deposited more slowly and bead conformation was irregular. Once again, the behavior mentioned was less marked for AC than for DC.

5.2 TRANSFER CHARACTERISTICS

“Spray” transfer was dominant with the six electrodes. In F position, 7.5%, 10%, 12.5% Calcite was faster than 15%, 17.5% and 20% Calcite. In all cases, transfer was faster on AC than on DC.

5.3 SPATTER

In general, spatter was moderate, medium sized, and cold (it was possible to remove by simple brushing). For DC (+), 15%, 17.5%, 20% Calcite presented higher spatter than 5%, 10%, 12.5% Calcite. This difference is less notable for AC.

5.4 OPERATIONAL PROPERTIES

According to the results of operational properties, all electrodes presented a stable arc for each type of current. The 15%-calcite arc is softer and visually shows lower penetration than 7.5%

calcite. This is probably due to the presence of cellulose in the 7.5% calcite coating. In all cases, the arc is well directed. The 15%, 17.5% and 20% calcite slag is thicker and more abundant than the one deposited by 7.5%, 10% and 12.5% calcite. The slag detachment is better for AC than DC. For AC, all electrodes showed slag self-detachment in F position. For DC (+) the slag was more difficult to take off, especially with 17.5% calcite. For this type of welding current, in F position, the slag cracked but did not self-detach.

Table 5.1 Observations of porosity, arc stability, slag detachability and smoke level during welding

Coating	Current type	Arc Stability	Smoke Level	Slag detachability	Porosity
	AC	Good	High	Good	Not present
Calcite 7.5%	DC (+)	Medium	High	Low	Present
	DC (-)	Excellent	Medium	Good	Present
	AC	Good	High	Good	Not present
Calcite 10%	DC (+)	Medium	High	Low	Extensively present
	DC (-)	Good	High	Moderate	Present
	AC	Excellent	Low	Good	Present
Calcite 12.5%	DC (+)	Average	Low	Low	Extensively present
	DC (-)	Excellent	Low	Low	Present
	AC	Good	Medium	Good	Present
Calcite 15%	DC (+)	Medium	Medium	Low	Present
	DC (-)	Excellent	Medium	Moderate	Present
	AC	Medium	Low	Good	Present
Calcite 17.5%	DC (+)	Average	Low	Low	Extensively present
	DC (-)	Excellent	Medium	Good	Present

Calcite	AC	Good	Low	Good	Present
20%	DC (+)	Average	Medium	Low	Present
	DC (-)	Excellent	Low	Moderate	Present

5.5 BEAD CHARACTERISTICS

All beads deposited for all types of current were well shaped with fine ripples. In F position, the best bead was achieved with 5%, 7.5% Calcite.

5.5.1 Weld Bead Geometry

Table 5.1 shows results for the weld bead measurements. It can be observed increasing flux basicity produced a reduction in both penetration and bead width for the three types of current used. In all cases, joint penetration and bead width were lower with AC than with DC welding. The flux basicity increase did not seem to have a clear effect on bead reinforcement. The weld beads obtained with varying composition (% wt.) of calcite on welding with DC (+) are shown in Figure 5.1. Figure 5.2 shows weld beads obtained with various compositions (% wt.) of calcite marked on the plates, and welding with DC (-). Figure 5.3 shows the weld beads obtained with AC.

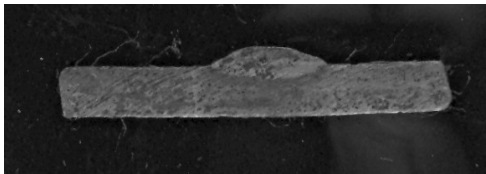
Table 5.2: Results for Weld Bead Geometry

	Current type	7.5% calcite	10% calcite	12.5% calcite	15% calcite	17.5% calcite	20% calcite
Bead width (mm)	AC	10.00	9.86	9.18	9.16	9.00	8.96
	DC (+)	10.40	9.96	9.50	9.30	9.28	9.12
	DC (-)	10.37	9.96	9.70	9.46	9.10	9.00
Bead reinforcement (mm)	AC	1.40	1.05	1.26	1.26	1.06	1.05
	DC(+)	1.80	1.86	1.76	1.50	1.43	1.43
	DC(-)	2.46	2.25	2.03	2.16	2.69	2.10
Penetration (mm)	AC	1.35	1.29	1.26	1.23	1.15	1.10
	DC(+)	1.66	1.56	1.46	1.36	1.31	1.20

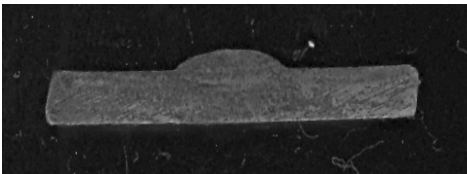
DC(-)	1.76	1.60	1.53	1.47	1.38	1.36
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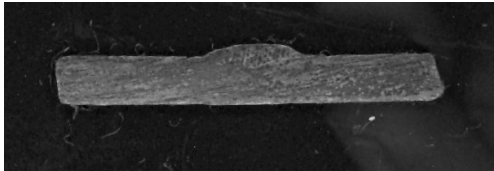
Figure 5.1 Weld bead obtained on Welding with AC



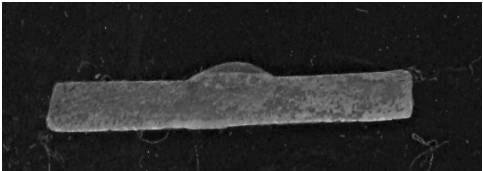
7.5 AC



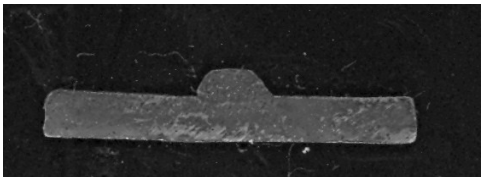
10 AC



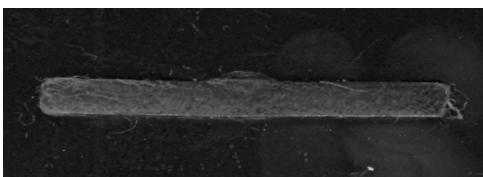
12.5 AC



15 AC



17.5 AC



20 AC

Fig 5.2 Weld Bead Cross-section images

5.6 ALL-WELD METAL PROPERTIES

5.6.1 Chemical Composition Results

Table 5.3 presents the all-weld-metal chemical composition. The analysis samples were obtained from weld pads.

It was observed that as both flux CaCO_3 content and flux basicity increased the deposited metal Si content was decreased. This was probably due to the effect that decrease of coating SiO_2 content as it was replaced with CaCO_3 , which decreased the activity of Si that was transferred to the slag as oxide.

Table 5.3: Results for all Weld Metal Chemical Composition, AC

Element (wt %)	7.5% Calcite	10% Calcite	12.5% Calcite	15% Calcite	17.5% Calcite	20% Calcite	Base plate	Filler Wire
C	0.0195	0.172	0.226	0.186	0.233	0.211	0.328	0.150
Si	0.380	0.328	0.286	0.265	0.245	0.220	0.207	0.0168
Mn	0.387	0.400	0.402	0.396	0.390	0.406	0.501	0.354
P	0.0526	0.0496	0.0506	0.0509	0.0043	0.0614	0.0501	0.0414
S	0.0362	0.0376	0.0357	0.0503	0.0196	0.0340	0.0800	0.0459
Cr	0.0236	0.0280	0.0435	0.0430	0.0590	0.0580	0.0010	0.0038
Ni	0.0074	0.0050	0.0095	0.0050	0.0050	0.0087	0.159	0.112
Al	0.0016	0.0010	0.0012	0.0010	0.0028	0.0022	0.0857	0.0010
Nb	0.0060	0.0029	0.0075	0.0025	0.0080	0.0071	0.0010	0.0020
Ti	0.0066	0.0070	0.0723	0.0662	0.0138	0.0088	0.0157	0.0123
V	0.0070	0.0088	0.0071	0.0086	0.0088	0.0076	0.0050	0.0083

Table 5.4: All Weld Metal Chemical Composition, DC (+)

Element (wt %)	7.5% Calcite	10% Calcite	12.5% Calcite	15% Calcite	17.5% Calcite	20% Calcite	Base plate	Filler Wire
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C	0.168	0.163	0.160	0.176	0.167	0.211	0.328	0.150
Si	0.310	0.305	0.294	0.280	0.270	0.254	0.207	0.0168
Mn	0.373	0.374	0.389	0.387	0.379	0.376	0.501	0.354
P	0.0390	0.330	0.0331	0.0509	0.332	0.0514	0.0501	0.0414
S	0.0435	0.0363	0.0374	0.0433	0.0376	0.0340	0.0800	0.0459
Cr	0.0163	0.0040	0.0030	0.0029	0.0036	0.0080	0.0010	0.0038
Ni	0.0050	0.0010	0.0010	0.0010	0.0010	0.0010	0.159	0.112
Al	0.0010	0.0056	0.0055	0.0010	0.0055	0.0022	0.0857	0.0010
Nb	0.0468	0.0056	0.0058	0.0065	0.0053	0.0071	0.0010	0.0020
Ti	0.0077	0.0039	0.0045	0.0062	0.0065	0.0088	0.0157	0.0123
V	0.0135	0.0020	0.0020	0.0020	0.0020	0.0020	0.0050	0.0083

Table 5.5: All Weld Metal Chemical Composition, DC (-)

Element (wt %)	7.5% Calcite	10% Calcite	12.5% Calcite	15% Calcite	17.5% Calcite	20% Calcite	Base plate	Filler Wire
C	0.288	0.163	0.184	0.133	0.167	0.265	0.328	0.150
Si	0.373	0.356	0.310	0.280	0.264	0.243	0.207	0.0168
Mn	0.372	0.381	0.371	0.385	0.379	0.388	0.501	0.354
P	0.0232	0.330	0.523	0.0245	0.332	0.0518	0.0501	0.0414
S	0.0354	0.369	0.150	0.0303	0.0376	0.0344	0.0800	0.0459
Cr	0.004	0.0040	0.182	0.003	0.0039	0.0709	0.0010	0.0038
Ni	0.006	0.0010	0.305	0.005	0.0010	0.0354	0.159	0.112
Al	0.0013	0.0056	0.102	0.001	0.003	0.0010	0.0857	0.0010
Nb	0.006	0.0056	0.0072	0.006	0.0053	0.071	0.0010	0.0020
Ti	0.114	0.0039	0.125	0.0129	0.0065	0.0114	0.0157	0.0123
V	0.0020	0.0020	0.0539	0.0020	0.0020	0.0020	0.0050	0.0083

The Mn contents were approximately the same for each type of current in spite of the increase in slag basicity, because the Mn powder content of the coatings was adjusted to obtain these results to avoid introducing another variable to the system.

Cr, Ni, and Ti values were not markedly affected by changes in flux basicity. Nb and V (probably coming from rutile) increased their values as flux basicity increased. Al levels were so low it was not possible to observe any effect.

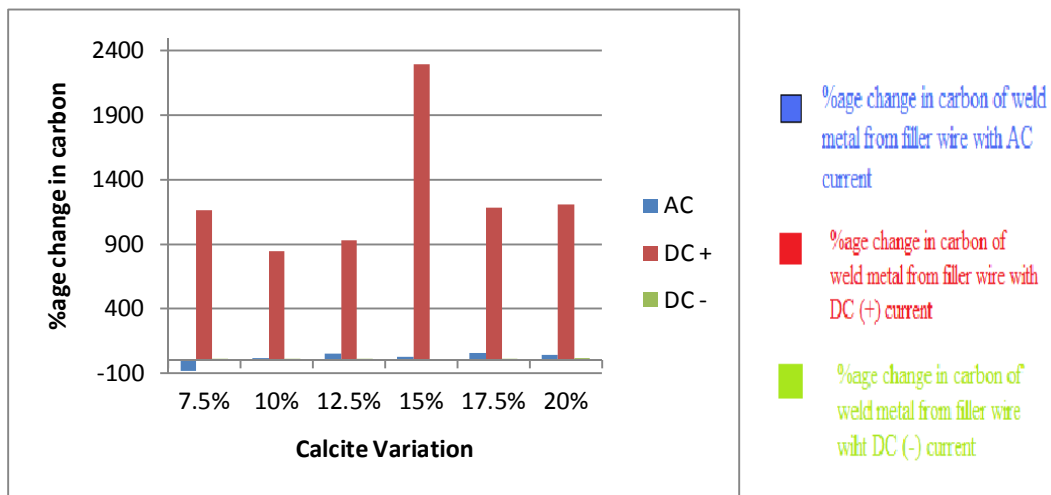


Fig 5.3 Percentage variation of Carbon w.r.t. Calcite Variation and type of current

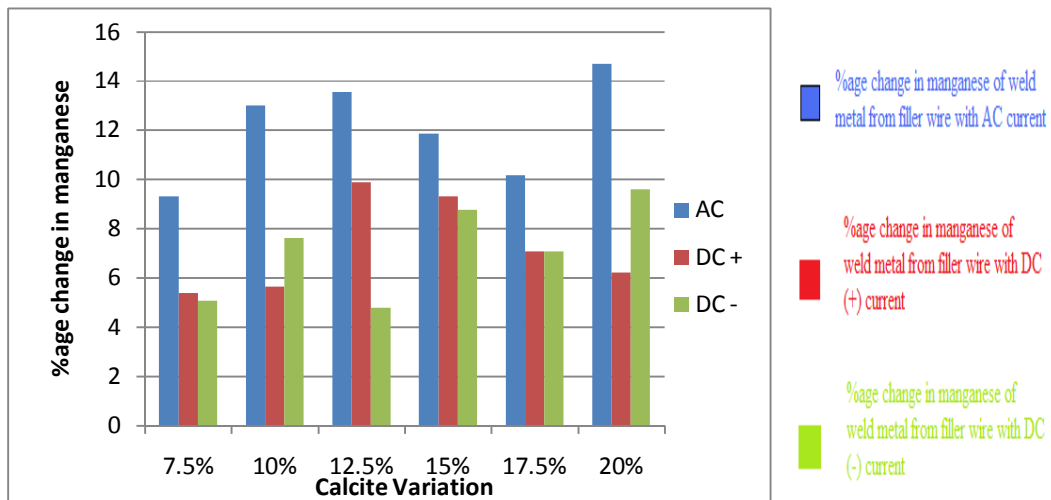


Fig 5.4 Percentage variation of Manganese w.r.t. Calcite Variation and type of current

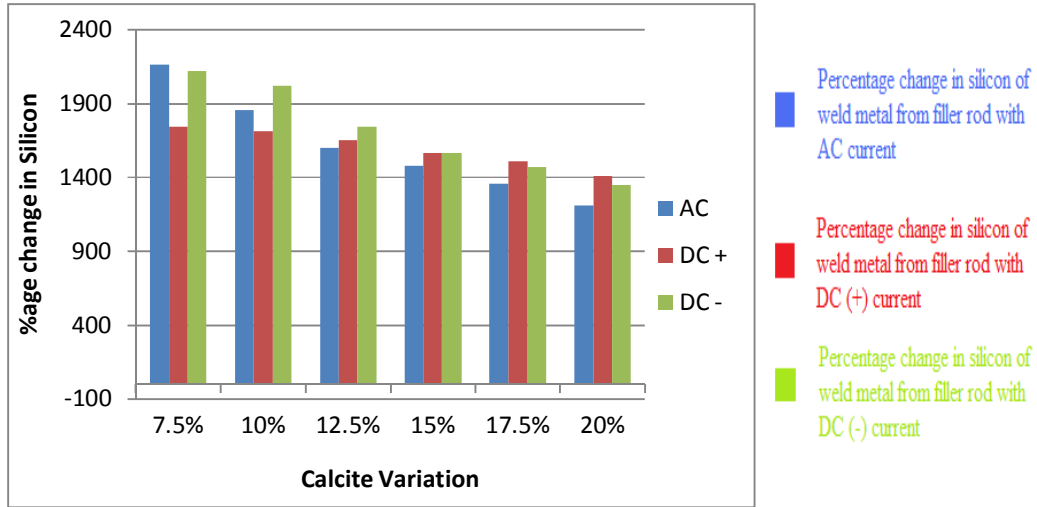


Fig 5.5 Percentage variation of Silicon w.r.t. Calcite Variation and type of current

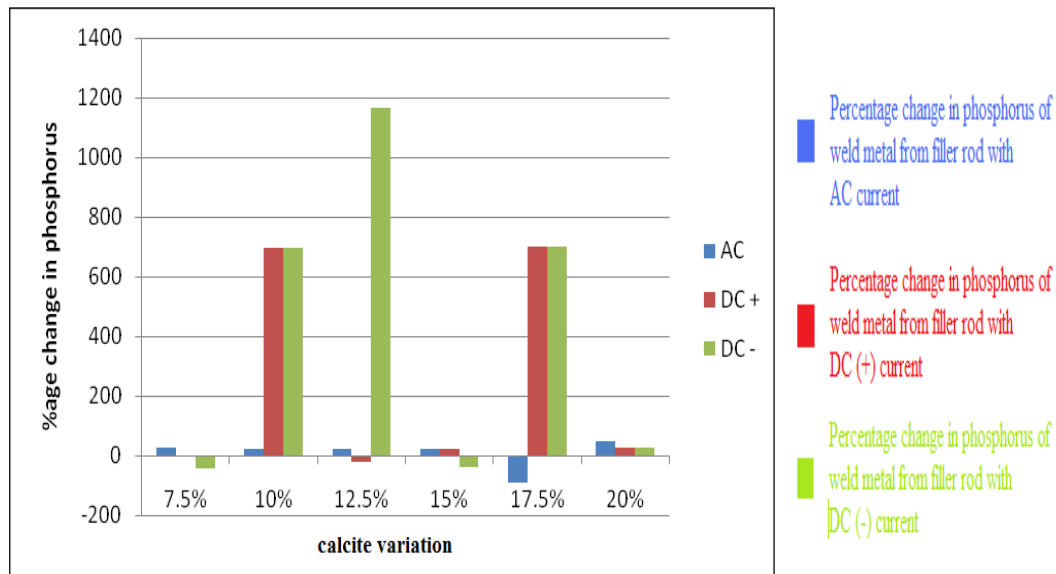


Fig 5.6 Percentage variation of Phosphorus w.r.t. Calcite Variation and type of current

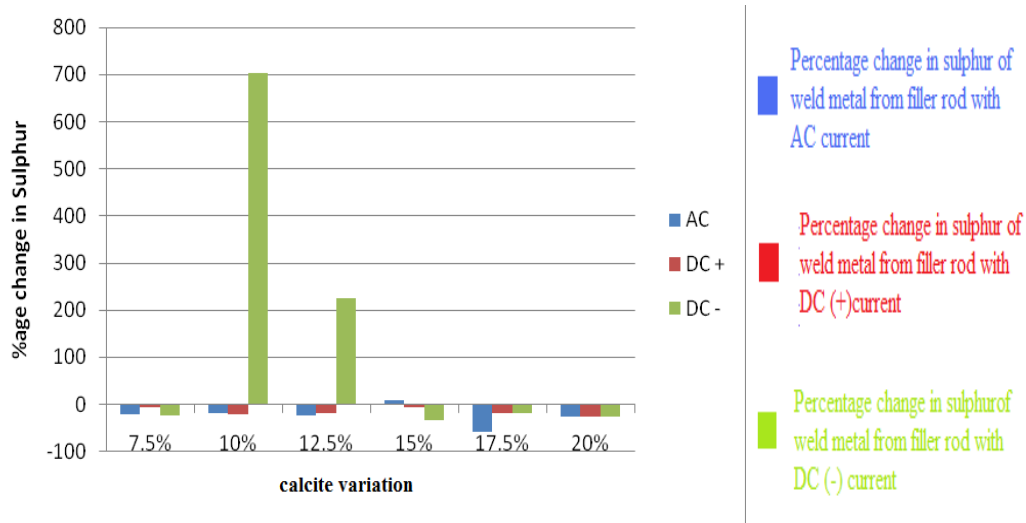


Fig 5.7 Percentage variation of Sulphur w.r.t. Calcite Variation and type of current

5.7 MECHANICAL PROPERTIES

5.7.1 Microhardness Measurements

Table 5.6 shows microhardness values obtained from different weld metal from the various coatings. It was observed that as flux basicity increased, the microhardness values decreased in each zone, probably due to the decrease of C and Si. The averages obtained showed the same trend: microhardness decreased with increments in slag basicity.

Table 5.6 Microhardness Test Results (MVH)

Base	7.5%	10%	12.5%	15%	17.5%	20%	
Plate	Calcite	Calcite	Calcite	Calcite	Calcite	Calcite	
	26.5	33.57	32.57	31.57	30.46	27.02	26.4

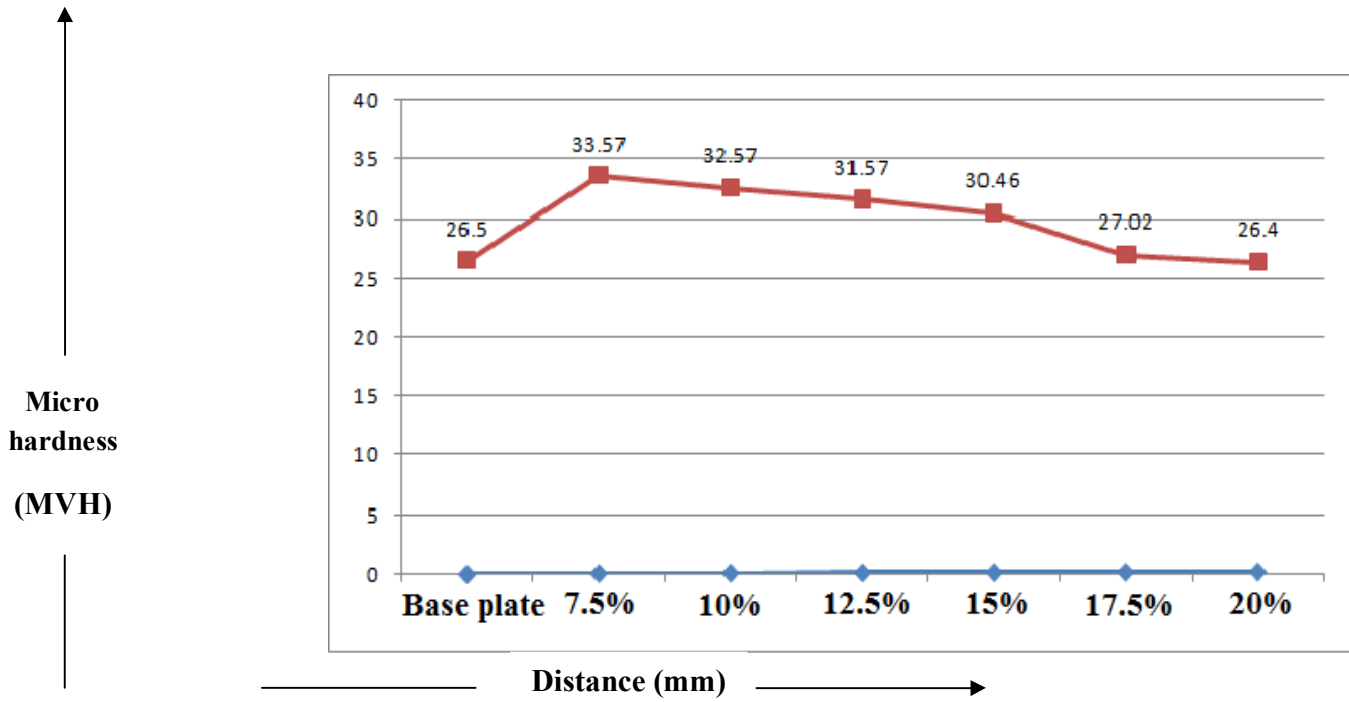


Fig 5.8 Microhardness Vs Calcite Composition

5.7.2 Tensile Properties



Fig 5.9 Tensile Weldment Specimen Gripped on UTM

Table 5.7 All Weld Metal Tensile Property Measurements

Property	7.5%	10%	12.5%	15%
Requirements	Calcite	Calcite	Calcite	Calcite
Elongation (%)	22	17	11	18
Yield Strength (N/mm²)	323	320	250	300
Tensile Strength (N/mm²)	430	425	323	376

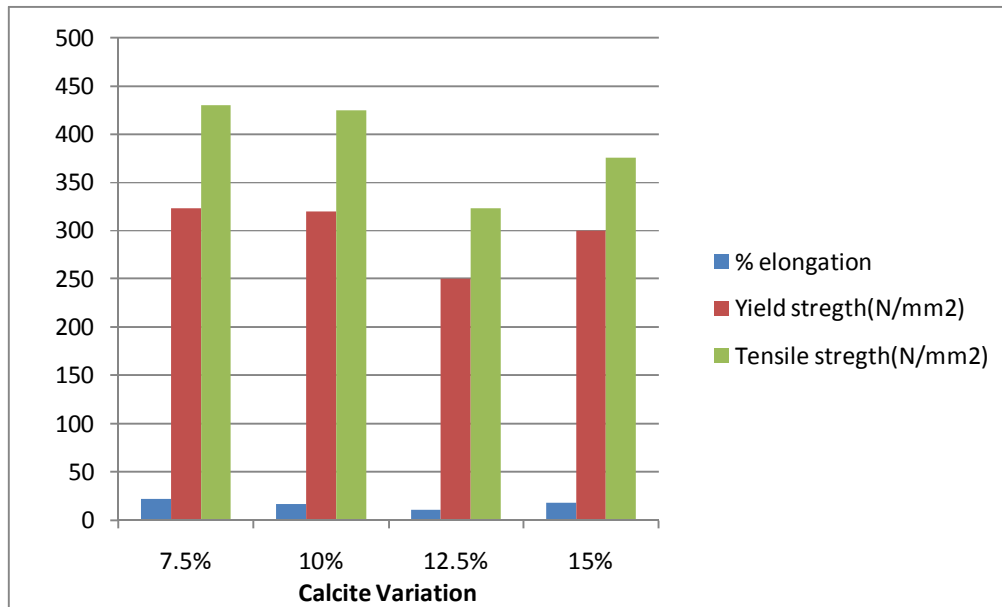


Fig 5.10 Histogram for Tensile Properties Measurements

Table 5.7 presents tensile property results of all weld metals. A decrease in tensile and yield strengths were observed as Si content of the weld decreased accompanied by a decrease in hardness.

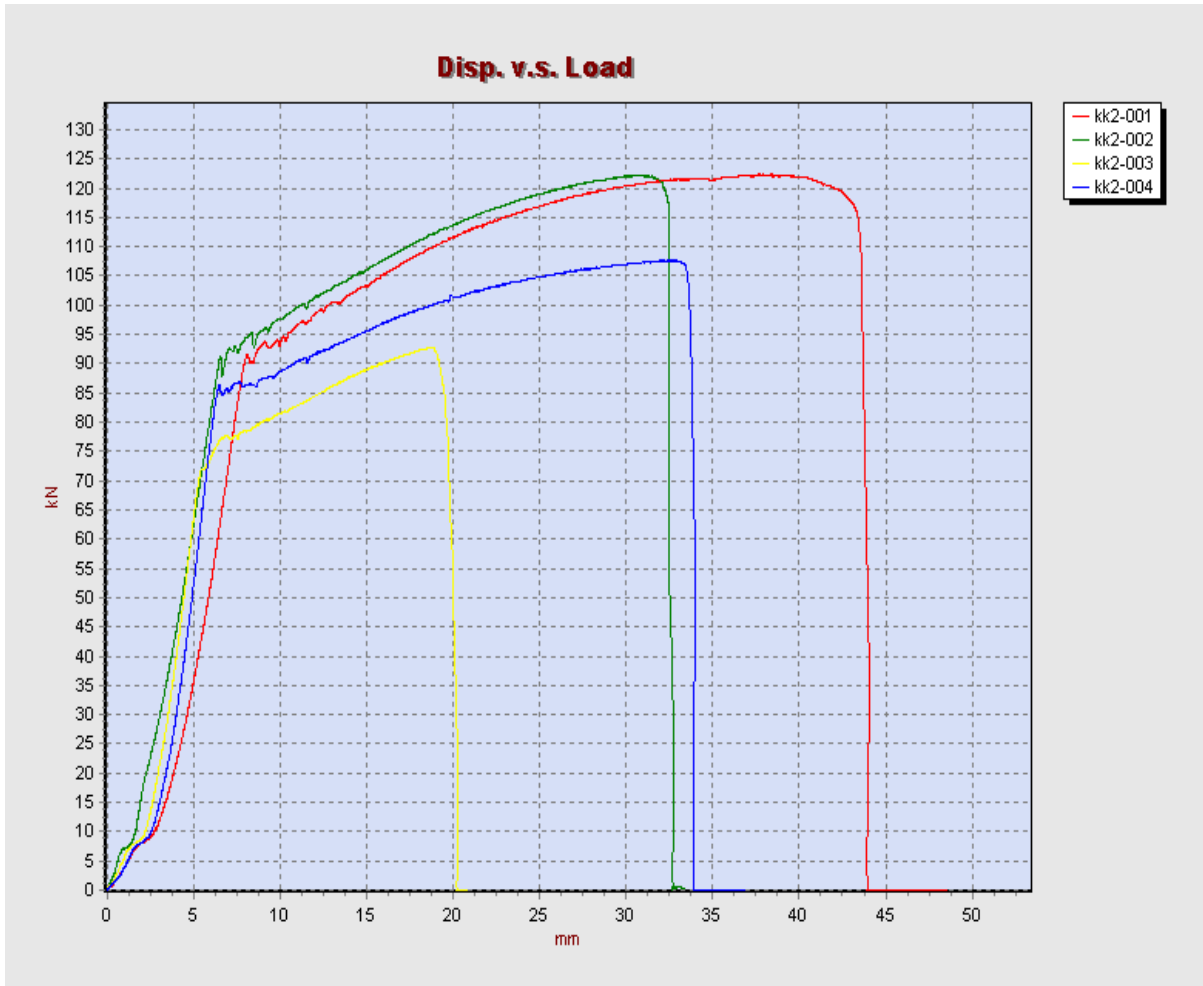


Fig 5.11 Load Vs Displacement Curve for Various Coatings

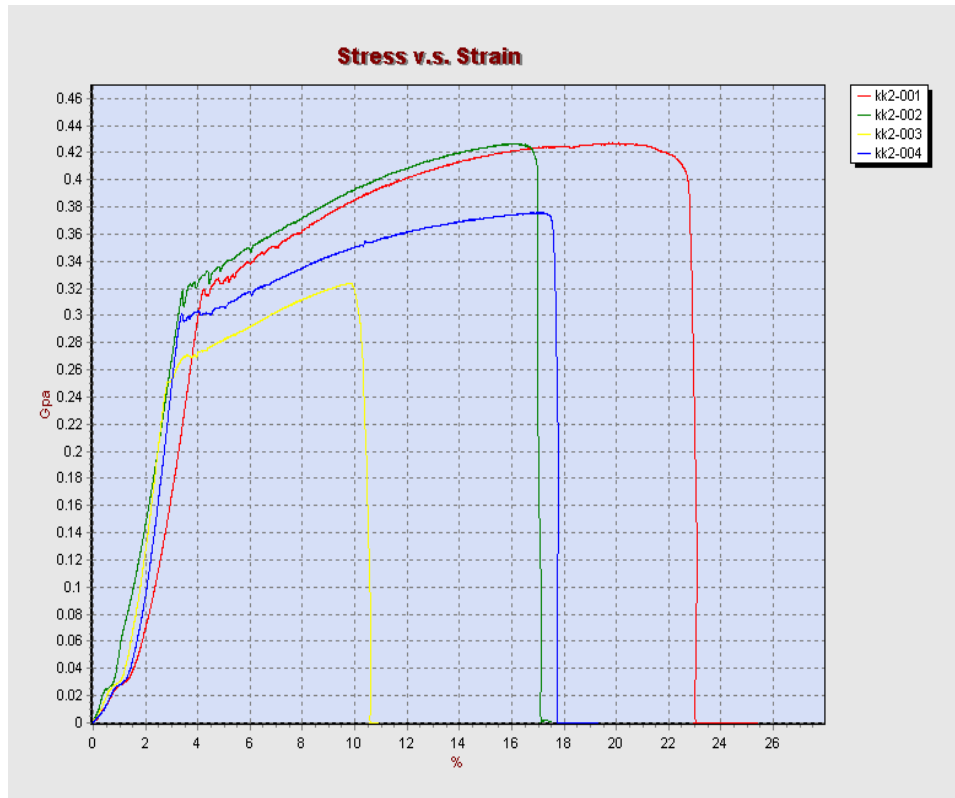


Fig 5.12 Stress v.s. Strain Curve for Various Coatings

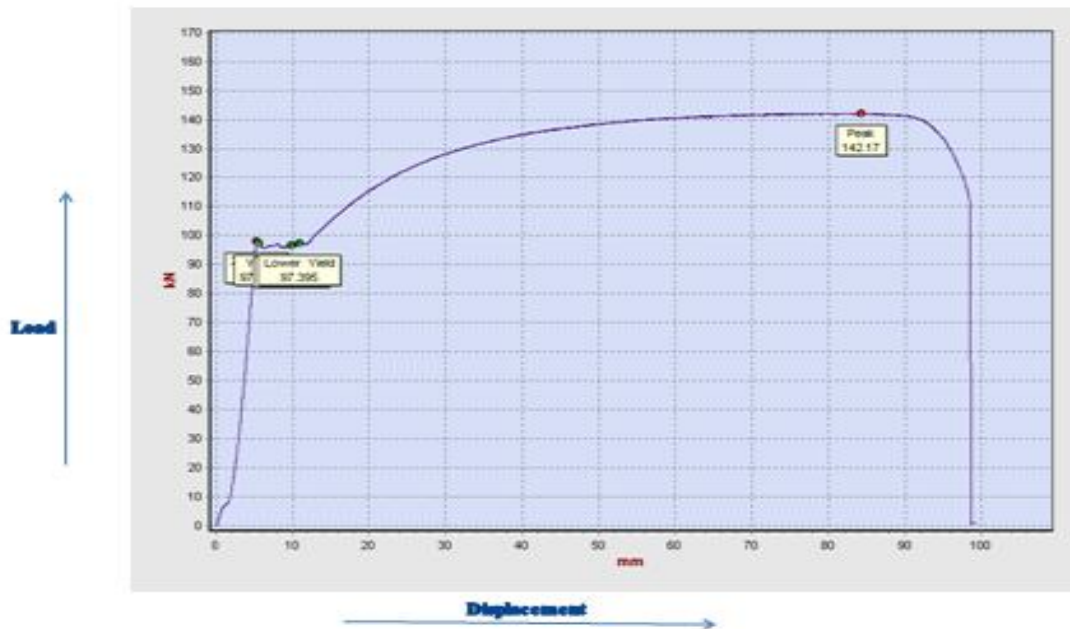


Fig 5.13 Load Vs Displacement Curve of Base Plate

5.7.3 Charpy V Notch Impact Test Results

It is generally accepted that toughness is related to several factors: nitrogen content, hardness level, tensile properties, type and quantity of inclusions.

In this case, the toughness increase does not seem to be accompanied by significant microstructural variations. Only the inclusion chemical compositions varied with slag basicity; however, this variation was not reflected in microstructural changes, as happens when Ti is varied. So, this increment of toughness appears to be related to the decrease in tensile properties and microhardness values associated with the decrease in deposited metal Si content, which was shown to be detrimental to toughness in this system.

Liquid nitrogen is used to drop the temperature of the specimen from room temp to -40° , -30° , -20° , -10° , 0°C , by varying the dipping time of specimen in liquid nitrogen. Thermometer is used to measure the temperature drop of the specimens. Then these specimens were tested in impact testing machine and the results were recorded.



Fig 5.14 Specimen Dipped in Liquid Nitrogen and Temperature measured with thermometer

Table 5.8 All Weld Metal Charpy V Notch Impact Test Results (Joule)

Test Average Temperature (°C)	7.5% Calcite		10% Calcite		12.5% Calcite	
	Charpy V	Average	Charpy V	Average	Charpy V	Average
-40	10-9-6-7-8	8	10-7-6-8-9	8	14-13-15-12-16	14
-30	7-18-10-6-9	10	7-9-11-13-20	12	13-16-17-20-24	19
-20	10-14-22-27-32	21	23-15-17-11-19	17	40-42-45-56-32	43
-10	20-25-18-30-37	26	15-58-25-42-30	34	55-57-52-43-73	56
0	35-37-42-43-48	41	50-37-75-27-61	50	56-78-39-69-48	58
30	48-57-69-74-77	65	67-77-87-85-89	81	103-76-88-79-99	89

Test Avg. Temp. (°C)	15% Calcite		17.5% Calcite		20% Calcite		Base Plate	
	Charpy V	Av.	Charpy V	Av.	Charpy V	Av.	Charpy V	Av.
-40	10-20-20-12-18	16	10-9-22-26-23	18	8-11-26-37-23	21	15-8-18-24-10	15
-30	31-35-25-22-42	31	43-36-49-27-55	42	40-59-64-76-46	57	19-27-23-14-32	23
-20	58-67-83-46-51	61	86-79-65-58-97	77	90-85-70-101-74	84	49-52-40-33-61	47
-10	58-83-81-47-91	72	67-97-86-75-110	87	95-101-99-111-89	99	55-58-71-39-47	54
0	60-66-79-57-83	69	69-76-90-64-81	76	75-84-99-71-91	84	57-78-36-51-83	61
30	102-89-98-117-79	97	115-123-109-84-89	104	119-104-134-149-89	119	92-67-83-79-114	87

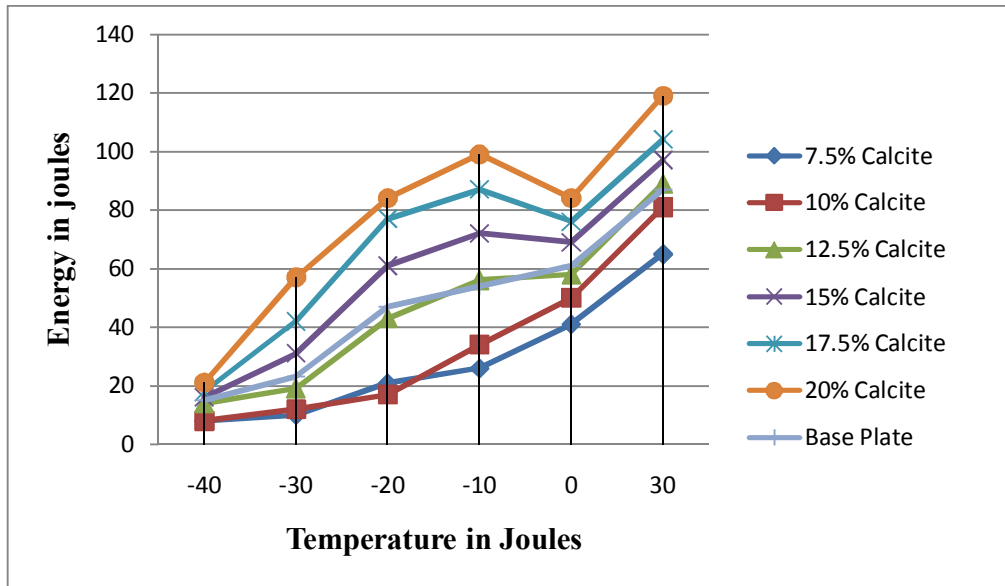


Fig 5.15 Energy Vs Temperature Graph of Impact Test Results

5.8 Smoke Test Results

Smoke test was performed to measure the smoke levels that were generated while welding on the specimen. CaF_2 was added in different quantities to six electrodes to reduce the smoke levels. It was observed that the smoke level was lesser in the 12.5 %, 17.5% and 20% calcite coating by the elimination of cellulose from the coating as compared to 7.5%, 10% and 15% calcite.

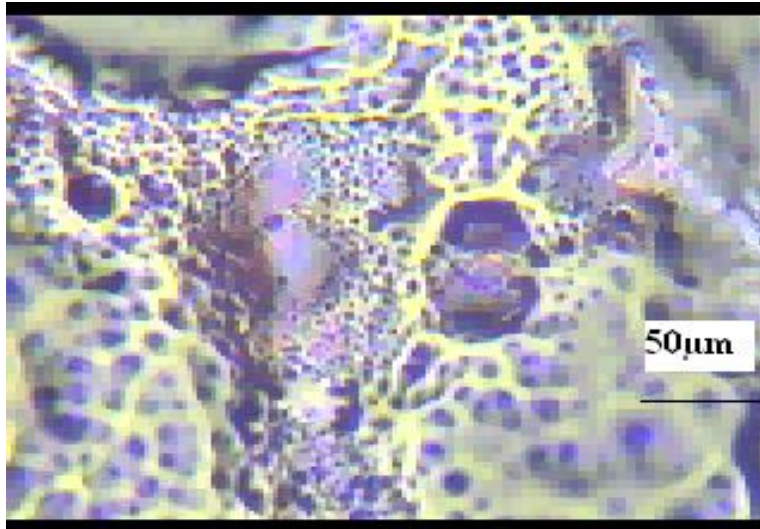
Table 5.9 Smoke Test Results

7.5% Calcite	10% Calcite	12.5% Calcite	15% Calcite	17.5% Calcite	20% Calcite
1.08	1.02	0.81	0.96	0.84	0.80

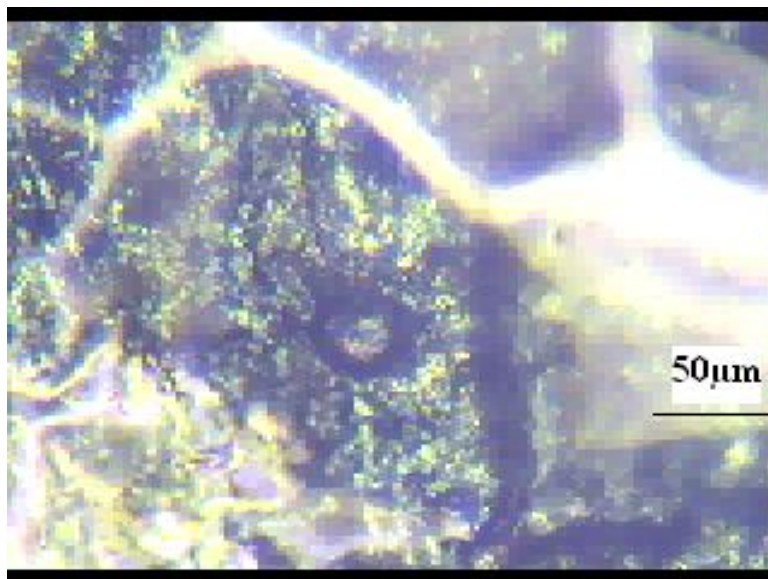
5.9 Microstructure Testing Results

The six electrodes were used with the same heat input. The 17.5% and 20% calcite electrode presented lower penetration resulting from the elimination of cellulose from the coating.

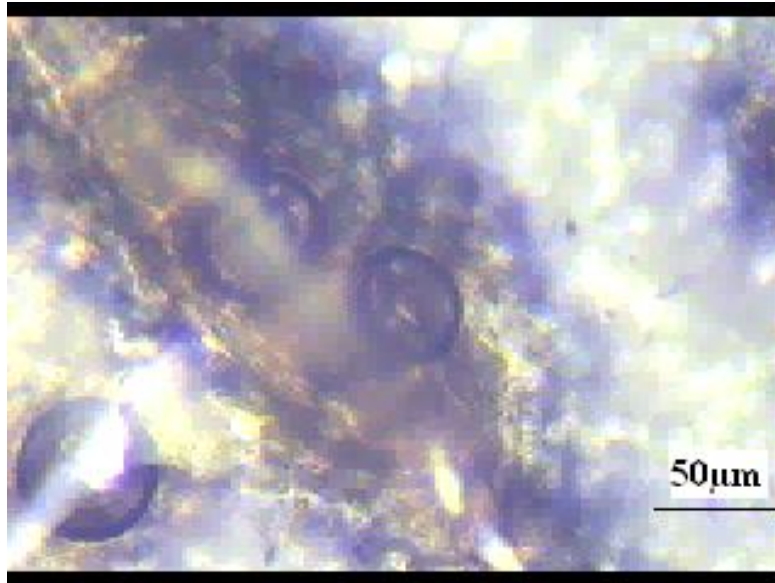
The optical micro structural at 200X did not provide much information on the weld grain orientation and grain size. Though columnar Re-orientation is apparent but still the micro structural examination does not provide much conclusive information about weld solidification process. It only indicates presence of inclusions and secondary phase particles.



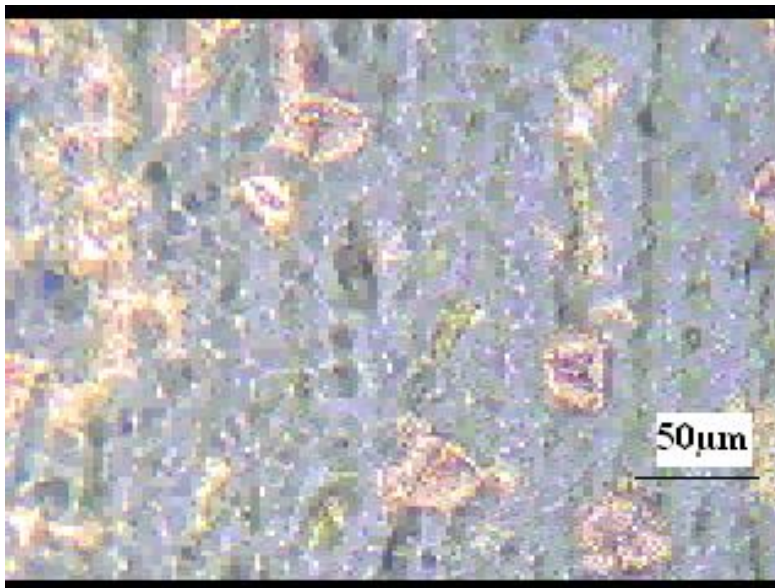
5.16 Micro structure of 7.5% Calcite with AC at 200 X



5.17 Micro structure of 10% Calcite with AC at 200 X



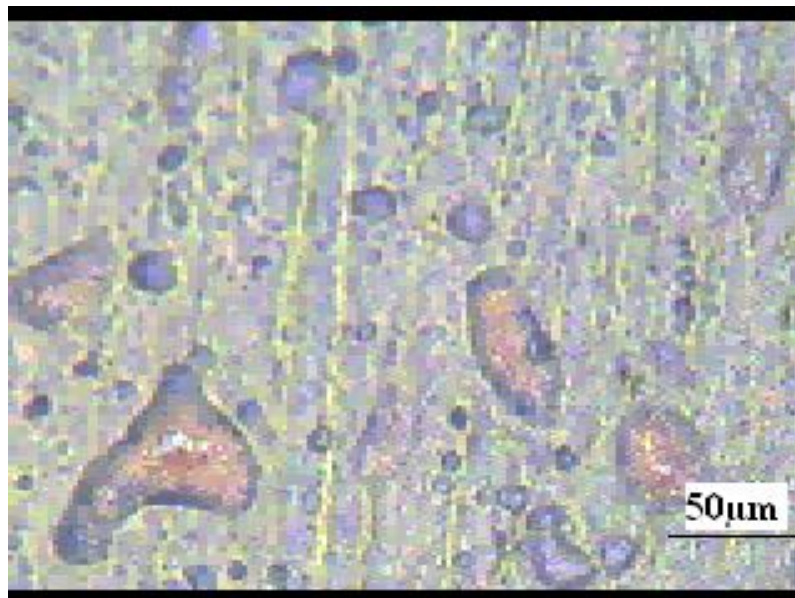
5.18 Micro structure of 12.5% Calcite with AC at 200 X



5.19 Micro structure of 15% Calcite with AC at 200 X



5.20 Micro structure of 17.5% Calcite with AC at 200 X



5.21 Micro structure of 20% Calcite with AC at 200 X



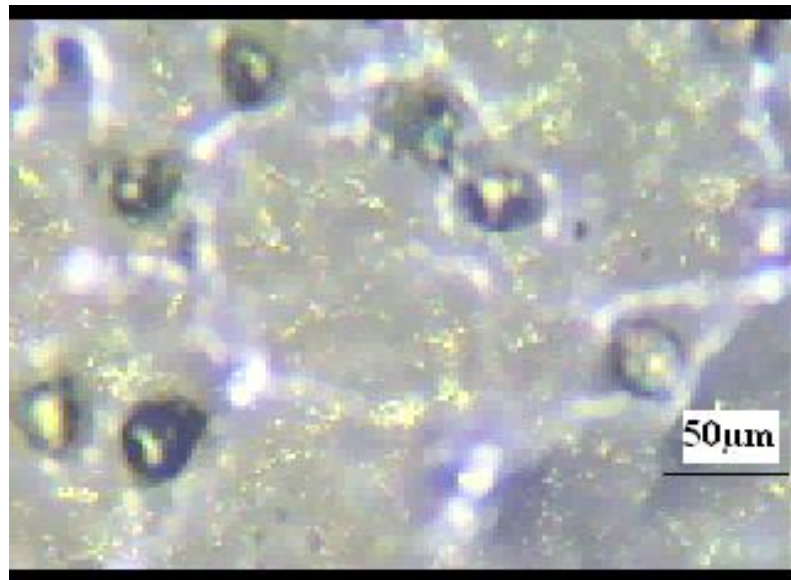
5.22 Micro structure of 7.5% Calcite with DC(-) at 200 X



5.23 Micro structure of 10% Calcite with DC(-) at 200 X



5.24 Micro structure of 12.5% Calcite with DC(-) at 200 X



5.25 Micro structure of 15% Calcite with DC(-) at 200 X



5.26 Micro structure of 17.5% Calcite with DC(-) at 200 X



5.27 Micro structure of 20% Calcite with DC(-) at 200 X

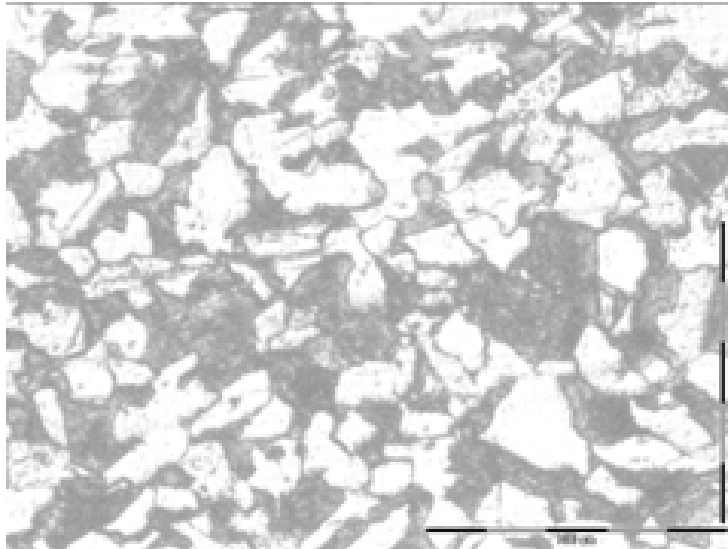


Fig 5.28 Microstructure of Base Plate at 200 X

CHAPTER 6

CONCLUSION AND SCOPE OF

FUTURE WORK

The coating composition of a Rutile electrodes was modified by increasing calcite content by incrementally increase flux basicity. As flux basicity increased, the following results were observed:

1. A slight deterioration of operational properties in the flat position was observed. This effect is less noticeable for AC than DC. Joint penetration and bead width decreased. In general, the rutile electrode operational behavior was maintained, but to obtain good operational properties, it was necessary to increase welding current as basicity increased.

2. A decrease in all-weld-metal Si content is observed.
3. No important micro structural changes were observed by optical microscopy.
4. A slight decrease in micro hardness values with increase in basicity is observed.
5. A reduction in tensile property values is observed with increase in basicity of flux.
6. A very important increase in toughness properties with increase in basicity.
7. Reduction in Smoke level is due to the elimination of cellulose from the coating electrode.

Further work can be carried out by varying the basicity index and by using other fluxes.

The present work was carried out by using the C-Mn Structural Steel. Other Steels can also be used.

CHAPTER 7

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