DISSERTATION REPORT

ON

STUDY THE EFFECT OF SENSITIZATION ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AISI 304 SS JOINTS USING GTAW PROCESS.

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF

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CERTIFICATE

This is certify that the thesis report entitled **"Study the effect of sensitization on the microstructure and mechanical properties of AISI 304 SS joints using GTAW process."** being submitted by Mr. Viranshu Kumar to Lovely Professional university, Phagwara, Punjab, in partial fulfilment of the requirement for the award of the Degree of Master of Technology (Spl. in Manufacturing Technology) is a record of student's own work carried my supervision and guidance.

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(Mr. Hitesh Arora)
Supervisor

The M-Tech Dissertation internal examination has been held on ……

Signature of Examiner
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(External)

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Date:

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Abstract

SS 304 is Austenitic stainless steel (ASS) with Nickel and Chromium as basic constituents. It has very good weldability and corrosion resistance. Austenitic stainless steels form chromium depleted zones at the grain boundaries during heat treatment and welding, where carbon combines with chromium and form chromium carbide at the grain boundaries. This phenomenon is known as sensitization.

The objective of this dissertation is to study the effect of sensitization on the microstructure and mechanical properties such as microhardness, impact strength, yield strength and tensile strength of an austenitic stainless steel. Samples of the steel have been given sensitization treatment by holding at 750° C to 1000° C temperature for different soaking time periods ranging from 0.5 to 2 hours followed by normalizing. The microstructures of sensitized samples have been observed by optical microscope. The mechanical testing such as micro hardness, impact test, and tensile testing of each specimen has been performed. The micro hardness, impact strength and tensile strength of the investigated stainless steel sharply decreases with increase in sensitization time, whereas the yield strength of this steel changes marginally with sensitization time.

Key Words: Carbide precipitation, GTAW, HAZ, Impact strength, Mechanical Properties, Microstructure, Micro hardness, Sensitization, SS 304, Tensile Strength.

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Nomenclature and Abbreviations

SS	Stainless steels
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
$M_{23}C_6$	M represents chromium and some small amount of iron, C for carbon
LTS	Low temperature sensitization
FCC	Face centered cubic
Bcc	Body centered cubic
IGC	Inter-granular corrosion
SCC	Stress corrosion cracking
TGSCC	Trans-granular stress corrosion cracking
IGSCC	Inter-granular stress corrosion cracking
U.T.S	Ultimate tensile strength
Y.S	Yield strength
MPa	Mega Pascal
DCEN	Direct current electrode negative
DCEP	Direct current electrode positive
AC	Alternating current
Q	Heat input
I	Welding current
S	Welding Speed
K	Thermal efficiency factor
Kj	kilo joules
Kj/mm	Heat input per unit length per pass

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Chapter 1
Introduction

1.1 Sensitization

Austenitic stainless steels are used in the nuclear, transportation, chemical, medical industry and pressure vessels due to their superior mechanical properties and corrosion resistance [1]. Stainless steel (Austenitic) are nickel chromium alloys with face centered cubic crystal structure having chromium content more than 12 wt. %. These steel exhibit good ductility, formability and better yield strength. Austenitic stainless steels are most commonly used due to its low temperature toughness and high corrosion resistance [2]. Welding is the joining processes in the mechanical industry and the properties of the weldments are significantly different to the base metal. This may sometimes cause to the failure of the component. Sensitization of the weldments is one of the problems in the welding of ASS. Sensitization leads to degradation of mechanical properties and corrosion resistance of weldments [3, 4].

Sensitization is the degradation of corrosion resistance and mechanical properties due to depletion of chromium and precipitation of chromium rich carbide particles in the grain boundaries when the steel encounters temperatures in the range of about 450 °C to around 850 °C, most notably in the HAZ of a weld. [5]

Typically, the Cr carbide is Cr-enriched $M_{23}C_6$, in which M represents Cr and some small amount of Fe. Within the sensitization temperature range carbon atoms rapidly diffuse to grain boundaries, where they combine with Cr to form Cr carbide. Because of Cr carbide precipitation at the grain boundary, the areas adjacent to the grain boundary are depleted of Cr, as shown schematically in fig. 1.1

These areas become anodic to the rest of the grain and hence are preferentially attacked in corrosive media, resulting in intergranular corrosion. It was also observed that deformation prior to welding or strain during cooling can enhance sensitization, this is perhaps due to the fact that dislocations can increase the diffusion rate and carbide nucleation rate. [6]

The sensitization below the sensitization temperature range is termed low temperature sensitization (LTS). The pre-existing tiny carbide particles were observed to grow in size when failed components were investigated, this was accompanied by severe chromium depletion from adjacent grain boundaries. [7]

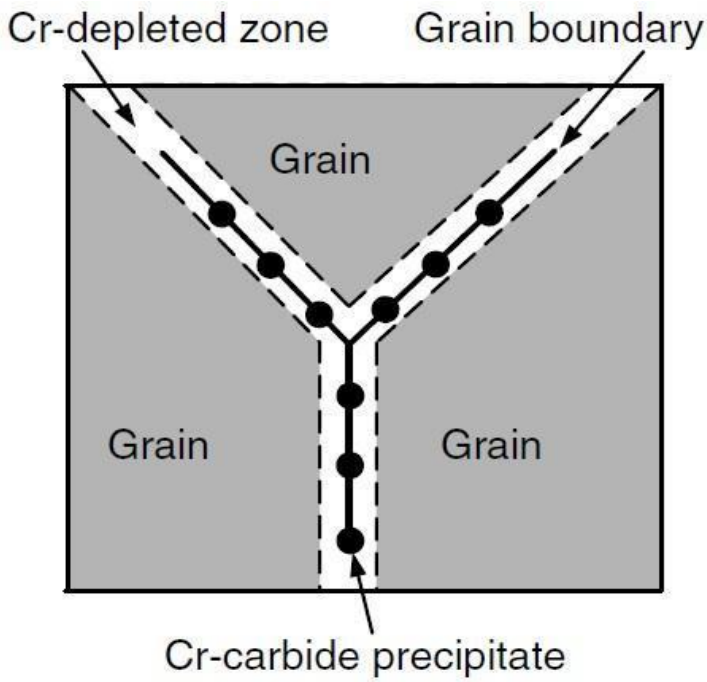


Figure 1.1 Grain boundary microstructure in sensitized austenitic stainless steel. [7]

When the intergranular corrosion propagates along grain boundaries from the surface into material, grain dropping may occur, leading to material mass loss as shown in fig. 1.2. [8]

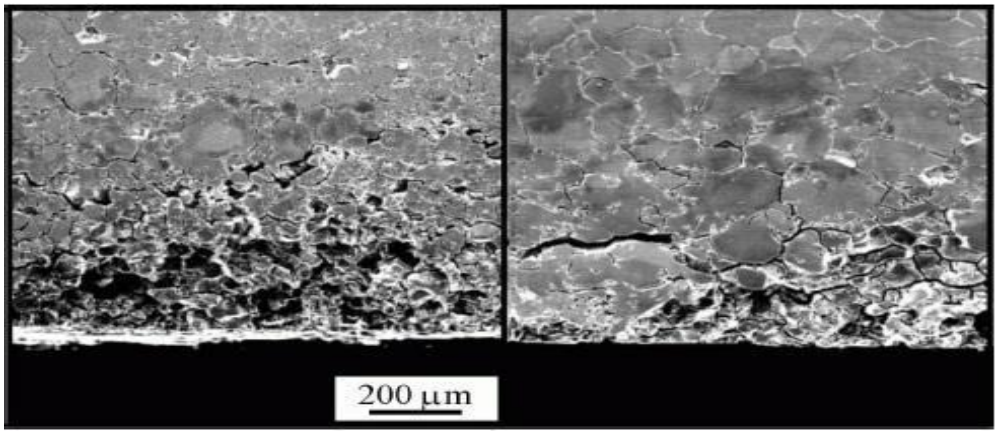


Figure 1.2. Micrographs showing grain dropping due to intergranular corrosion. [8]

Weld decay does not occur immediately next to the fusion boundary, where the peak temperature is highest during welding. Instead, it occurs at a short distance away from it, where the peak temperature is much lower. This phenomenon can be explained with the help of thermal cycles during welding, as shown in fig. 1.3. At position 1 near

the fusion boundary, the material experiences the highest peak temperature and cooling rate. Consequently, the cooling rate through the precipitation range is too high to allow Cr carbide precipitation to occur. At position 2, which is farther away from the fusion line, the retention time of the material in the sensitization temperature range is long enough for precipitation to take place. At position 3, outside the HAZ, the peak temperature is too low to allow any precipitation. [6]

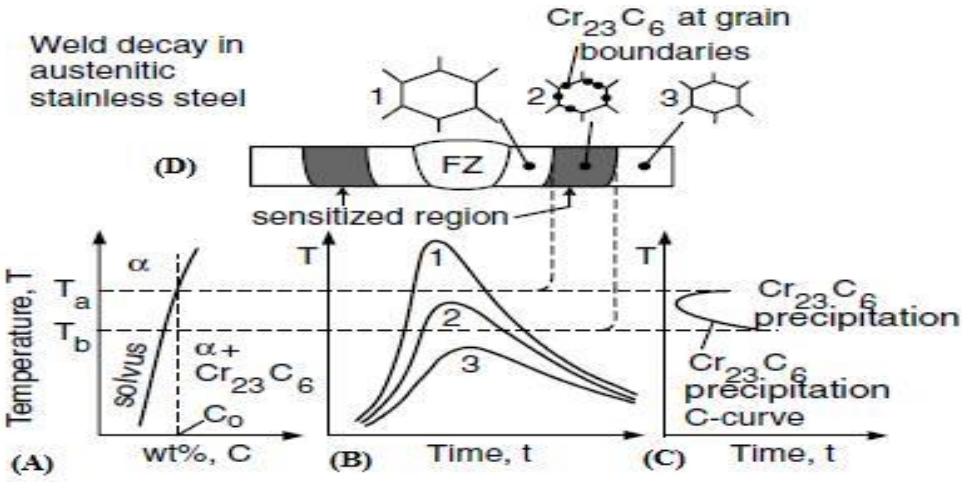


Figure 1.3. Sensitization in austenitic stainless steel: (A) phase diagram, (B) thermal Cycle, (C) precipitation curve, (D) microstructure. [6]

1.1.1 Remedies to Sensitization

Sensitization in austenitic stainless steels can be avoided as follows. [9]:

1. Reducing the time during which the temperature of the steel is in the 450 to 850°C range. This is done by rapid cooling and minimizing heat input during welding and heat treatment.

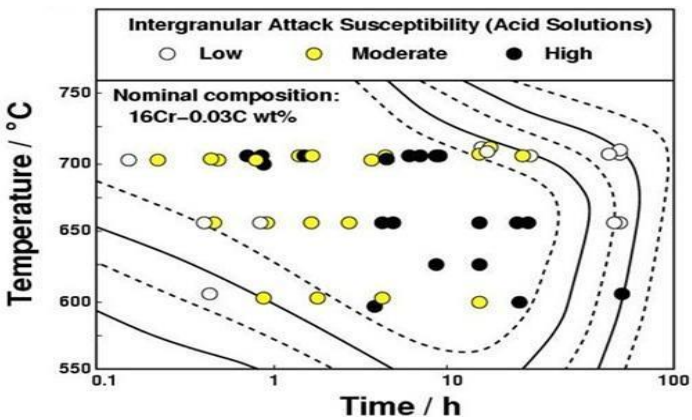


Figure 1.4. Time and temperature dependency of sensitization. [10]

2. Selecting the stainless steel (for welding) with lower carbon content because the lower the amount of carbon less is the effect.i.e. of forming chromium carbide. The effect increases as the % of carbon increases. Steels with small % of carbon take much longer time to form carbides (fig. 1.5).

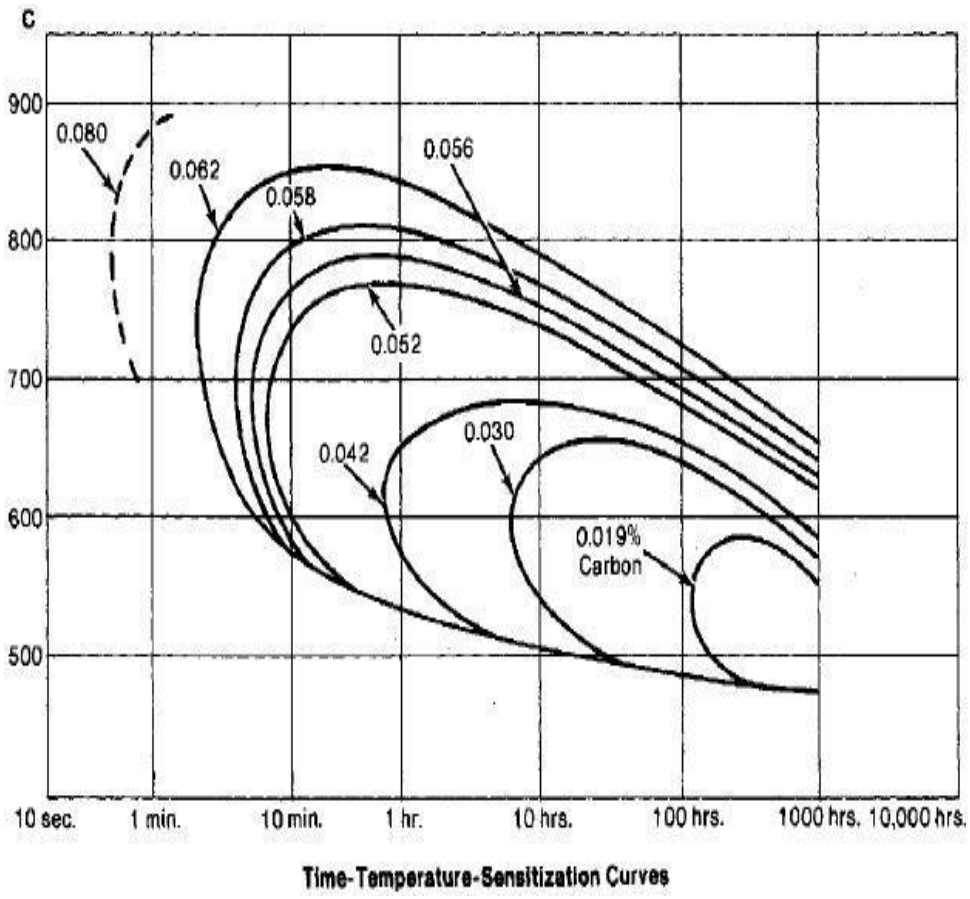


Figure 1.5. Effect of carbon contents in steel on the sensitization conditions. [11]

3. Addition of strong carbide formers, suitable additions of Niobium and Titanium. These elements prevent the formation of chromium carbides by forming titanium or niobium carbides.
4. Heat-treatment (quenching from more than1000 °C) of the welded structure also removes the intergranular corrosion in steel. This type of annealing heat treatment is done where high corrosion is required.

1.2 Material Used

SS 304 is selected for present stainless study steel family therefore attempt is made to describe stainless steels, austenitic stainless steels and SS 304 in this section of introduction.

1.2.1 Stainless Steel

A small amount of carbon alloyed with iron makes steel. Iron is allotropic in that it exists in at least two distinct crystalline forms, primarily dependent upon temperature. At high temperatures, the face centered cubic (FCC) crystal structure of iron is stable and the term used to describe this phase is austenite. [5]

Stainless steels are classes usually contain from 12 to 27% Cr and 1 to 2% Mn by weight, with the addition of Ni in some grades. A small amount of carbon is also present, either deliberately added or as an unavoidable impurity. [6] In general, they are alloyed with a number of other elements that make them resistant to a variety of different environments. These elements also modify the microstructure of alloy, which in turn has a distinct influence on their mechanical properties and weld ability. [12]

Cr provides the basic corrosion resistance to stainless steel. A thin layer of Cr-oxide from on the surface of metal when it is exposed to oxygen of the air. The film act as a barrier to further oxidation, rust and corrosion. [13] Stainless steels are extensively used in variety of applications where corrosion resistance is required in combination with good strength and toughness. [14] Stainless steel can be classified into three major categories based on the structure: Ferritic, Martensitic and Austenitic. [6]

1.2.2 Austenitic Stainless Steels

Among the various classes of stainless steels, the most easily welded are austenitic stainless steels. These steels contain typically 16-25% Cr, 7-20% Ni and less than 0.08% C. For improved corrosion resistance, 2-6% Mo, 0.1-0.2% N and niobium or titanium in the stabilized varieties are added. [14] Austenitic stainless steels are usually the most corrosion resistant of all the stainless steels and generally have low yield strength and high ultimate tensile strength that is why are often very ductile and has excellent properties at cryogenics temperature. [13]

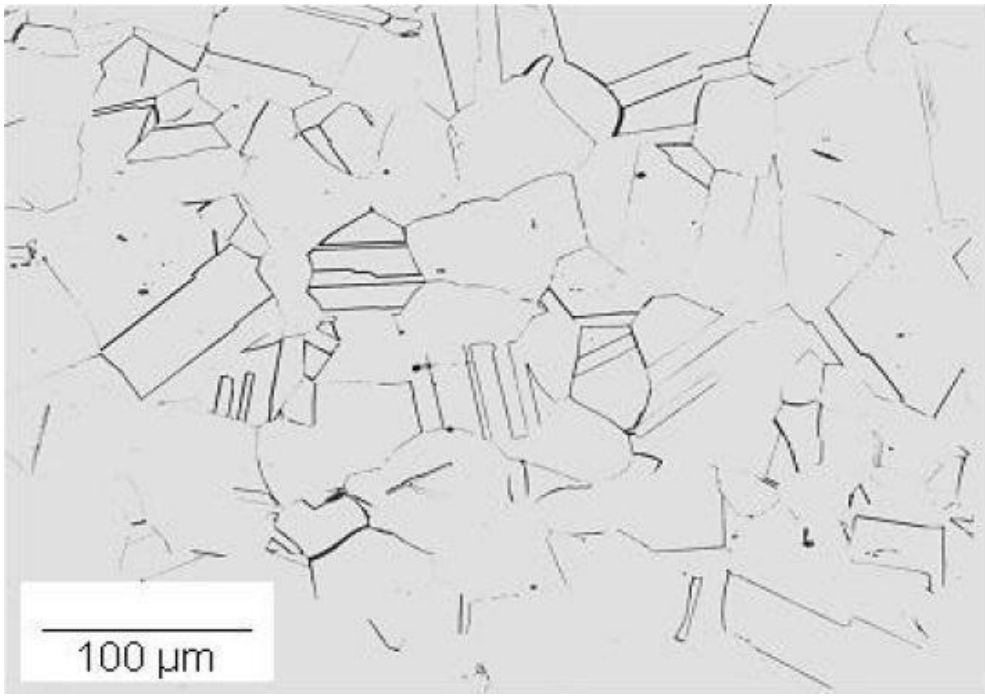


Figure 1.6 General microstructure of austenitic stainless steel. [8]

Alloying additions can also alter the temperature ranges where fcc and bcc is stable. Nickel atoms are nominally the same size as iron atoms and arrange themselves in the FCC structure over a significant temperature range. Therefore, substitution of nickel atoms for iron atoms makes the austenite phase stable to very low temperatures. Chromium atoms are bcc therefore, a large substitutionl addition of chromium to the steel has the effect of stabilizing the ferrite phase. Thus, when approximately 8% nickel and 18% chromium are alloyed with iron, the austenite phase is stabilized down to very low temperatures and an austenitic stainless steel is produced. Carbon and nitrogen atoms are smaller than the iron, chromium, or nickel atoms and occupy interstitial sites between the primary atoms in a given crystal. The unit cell structure of the austenite phase accommodates these interstitial atoms more readily than the unit cell structure of the ferrite phase. Therefore, carbon and nitrogen are very strong austenite stabilizers at relatively small volume fraction additions. Sulphur and phosphorus are considered trace impurity elements, remnant from primary and secondary processing. [5]

Austenitic stainless steels have excellent resistance to general corrosion. They are, however, prone to localized corrosion like crevice, pitting, intergranular corrosion (IGC), and stress corrosion cracking (SCC). While ASS is inherently prone to transgranular stress corrosion cracking (TGSCC) even in a solution-annealed

condition, certain microstructural features can make them prone to intergranular stress corrosion cracking (IGSCC). The two forms of localized corrosion, IGC and IGSCC, are directly caused by sensitization, which leads to precipitation of chromium rich carbides at the grain boundaries. Growth of such carbides can lead to the formation of chromium-depleted zones in the immediate surroundings. When the level of chromium in the depletion regions falls below 12-13 wt. %, the passive film over the depleted regions weakens and breaks easily in contact with aggressive solutions. The makes the sensitized ASS prone to IGC and IGSCC. [15] As the name implies the microstructure of austenitic stainless steel consists entirely of fine grains of austenite in the wrought condition. When subjected to welding, however, a secondary ferrite phase may be formed on the austenite grain boundaries, in the heat affected zone and in the weld metal. The extent of the formation of this secondary phase may depend on the composition of the steel or filler material and the heat input during welding. While delta ferrite formation can have negative effects on the resistance to corrosion and delta ferrite in weld metal is necessary to overcome the possibility of hot cracking (tearing). In general, austenitic welding consumables deposit a weldment containing 4–12% delta ferrite. For special applications (i.e. when dissimilar steels are welded under conditions of high restraint), austenitic consumables having weld metal delta ferrite contents as high as 40% may be required. [11]

When compared with common carbon steels, austenitic stainless steels exhibit significant differences viz. electrical resistance is about 6 times greater, melting point about 93^0C lower, thermal conductivity about 50% lower and thermal expansion is about 50% greater. The first three factors combine to make for lower welding current requirements (Table 1.1). [9]

These steels are most weld able of the S.S and can be divided rather loosely into three groups, Cr-Ni (300series), Mn-Cr-Ni-N (200 series) and specialty alloys. Austenite is most popular stainless group and is used for numerous industrial and consumer applications such as in chemical plants, power plants, food processing and dairy equipment's. Austenitic stainless steels had F.C.C structure, some grades can be prone to sensitization of the weld heat affected zone and weld metal hot cracking. [16]

Table 1.1 Influence of physical properties on welding austenitic stainless steel compared to carbon steel. [12]

Properties	**Austenitic stainless steel**	**Carbon Steel**	**Remarks**
Melting Point (Type 304)	1400 - 1450^{0}C	1540^{0}C	Type 304 requires less heat to produce fusion.
Magnetic response	Non-magnetic at all temperatures	Magnetic to over 750^{0}C	Nickel stainless steels are not subjected to arc blow.
Rate of conductivity	(Type 304)		Type 304 conducts heat much more slowly than carbon steel.
100^{0}C	28%	100%	
650^{0}C	66%	100%	
Electrical resistance (Annealed)			lower current,as compared to Carbon steel.
At 20^{0}C	72	12.5	
At 885^{0}C	126	125	

1.2.3 SS 304

The carbon content is kept to 0.08% or less to avoid the formation of chromium rich carbides during processing and especially during welding. A loss of free chromium by the formation of chromium-rich carbides can drastically reduce the local corrosion resistance and lead to preferential intergranular attack. If the carbon content in the steel is high (>0.03 wt. %), chromium-rich carbides may precipitate on grain boundaries in the weld heat affected zone. Such precipitation reduces the free chromium content and makes the heat affected zone (HAZ) susceptible to intergranular corrosion. Such condition reducing the amount of carbon available for the reaction with chromium, the

L grades of stainless steel have an enhanced resistance to weld HAZ sensitization. [16] Chromium is, of course, the primary element for forming the passive film (i.e. high-temperature, corrosion-resistance chromium oxide). Other elements can influence the effectiveness of chromium in forming or maintaining the film, but no other element can, by itself, create the stainless steel. Nickel in sufficient quantities, is used to stabilize the austenitic phase and to produce austenitic stainless steel. A corrosion benefit is obtained as well, especially in reducing environments. Nickel is particularly useful in promoting increased resistance to mineral acids. When nickel is increased to about 8 to 10% this is a level required to ensure austenitic structures in a stainless steel that has about 18% chromium. [4] Table 1.2 and 1.3 shows the chemical composition range and mechanical properties of SS 304 respectively.

Table 1.2 Composition ranges for 304 grade of stainless steels. [5]

	C	Mn	Si	P	S	Cr	Mo	Ni	N
Min.	-	-	-	-	-	18.0	2.00	10.0	-
Max.	.08	2.0	.75	.045	.03	20.0	3.00	14.0	.10

Table 1.3 Mechanical properties of 304 grade stainless steels at room temperature. [5]

U.T.S (MPa) min	Y.S 0.2% Proof (MPa) min	% Elongation (%in 50 mm) Min	Hardness	
			Rockwell Max	Brinell Max
515	205	40	92	202

Generally, the Alloy 304 and 304L grades can be considered to perform equally well for a given environment. A notable exception is in environments sufficiently corrosive to cause intergranular corrosion of welds and heat affected zones on susceptible alloys. In such media, the Alloy 304 grade is preferred for the welded condition since low carbon levels enhance resistance to intergranular corrosion. For applications where heavy cross sections cannot be annealed after welding or where low temperature stress relieving treatments are desired, the low carbon Alloys 304 is available to avoid the hazard of intergranular corrosion. This provides resistance to intergranular attack with any thickness in the as-welded condition or with short periods of exposure in 450 to 850° C temperature range. Where vessels require stress-relieving treatment, short treatments falling within these limits can be employed without affecting the normal excellent corrosion resistance of the metal. Accelerated cooling from higher temperatures for the "L" grades is not needed when very heavy or bulky sections have been annealed. [26]

Some of the typical applications of SS 304

- Nuclear industry.
- Pharmaceuticals.
- Marine applications.
- Chemical Industry.
- Architectural applications.

1.3 Welding Processes for Stainless Steels

The two basic methods for welding stainless steels are fusion welding and resistance welding. In fusion welding, heat is provided by an electric arc stuck between a carbon or metal electrode (connecting to one terminal of power supply) and the metal to be welded (which is connected to other terminal). In resistance welding, bonding is the result of heat and pressure. Heat is produced by the resistance of the flow of electric current trough the part to be welded, and pressure is applied by the electrodes. Both methods are widely used for the steels.

There are four types of fusion welding. They are:

1. Shielded Metal Arc Welding (SMAW)
2. Gas Tungsten Arc Welding (GTAW)

3. Gas Metal Arc Welding (GMAW)
4. Submerged Arc Welding (SAW)

Other fusion welding methods for stainless steels include plasma arc, electron beam and laser. In all cases, the weld zone is protected from the atmosphere by gases, slag or vacuum, which is absolutely necessary to achieve and preserve optimum corrosion resistance and mechanical properties in the joint. [12]

1.3.1 Welding Technique Used

GTAW is the process of choice for welding SS 304 because of following reasons.

1. However short period of high temperature exposure are uncounted, such as welding. If welding is done without excessive heat the changes in corrosion resistance and mechanical properties is expected to be minimum.
2. Because of properties of the material to be welded, ASS has poor thermal conductivity and higher thermal expansion, both of these factors can lead to distortion and cracking.

1.3.2 Gas Tungsten Arc Welding (GTAW)

Gas Tungsten Arc Welding, as the name suggests, is a process in which source of heat is arc forms between a non-consumable tungsten electrode and work piece, and the arc and the and the molten puddle are protected from atmospheric contamination (i.e. oxygen and nitrogen) with a gaseous shield of inert gas such argon, helium or argon-helium mixture. Filler metal, if required, is added externally to the arc in the form of bare wire by the welder. It is often referred to in abbreviated form as TIG Welding. Some authors prefer to call it inert-gas tungsten-arc welding. The American Welding Society refers to the process as a gas tungsten-arc-welding and has given it the letter designation GTAW. [2]GTAW easily welds all stainless steels and is particularly suited for welding stainless steel pipes, with or without an inert or backing ring. It is also used extensively in joining tubes to tube sheets in shell-and-tube heat exchangers [4].

Equipment's: Following are the equipment's used in GTAW. [14]

1. Welding Torch, Tungsten electrode and filler metal.
2. Welding Power source, high frequency unit, DC suply unit and cables.
3. Inert gas cylinder, pressure regulator and flow meter.

4. Cooling water supply.
5. Water and gas solenoid valves.

1.3.2.1 The Process

Gas–tungsten arc welding (GTAW) is a process that melts and joins metals by heating them with an arc established between a non-consumable tungsten electrode and the metals, as shown in fig. 1.7. The torch holding the tungsten electrode is connected to a shielding gas cylinder as well as one terminal of the power source, as shown in fig. 1.7A. The tungsten electrode is usually in contact with a water-cooled copper tube, called the contact tube, as shown in fig. 1.7B, which is connected to the welding cable (cable 1) from the terminal. This allows both the welding current from the power source to enter the electrode and the electrode to be cooled to prevent overheating. The workpiece is connected to the other terminal of the power source through a different cable (cable 2). The shielding gas goes through the torch body and is directed by a nozzle toward the weld pool to protect it from the air. Protection from the air is much better in GTAW than in SMAW because an inert gas such as argon or helium is usually used as the shielding gas and because the shielding gas is directed toward the weld pool. When a filler rod is needed, for instance, for joining thicker materials, it can be fed either manually or automatically into the arc. [4]

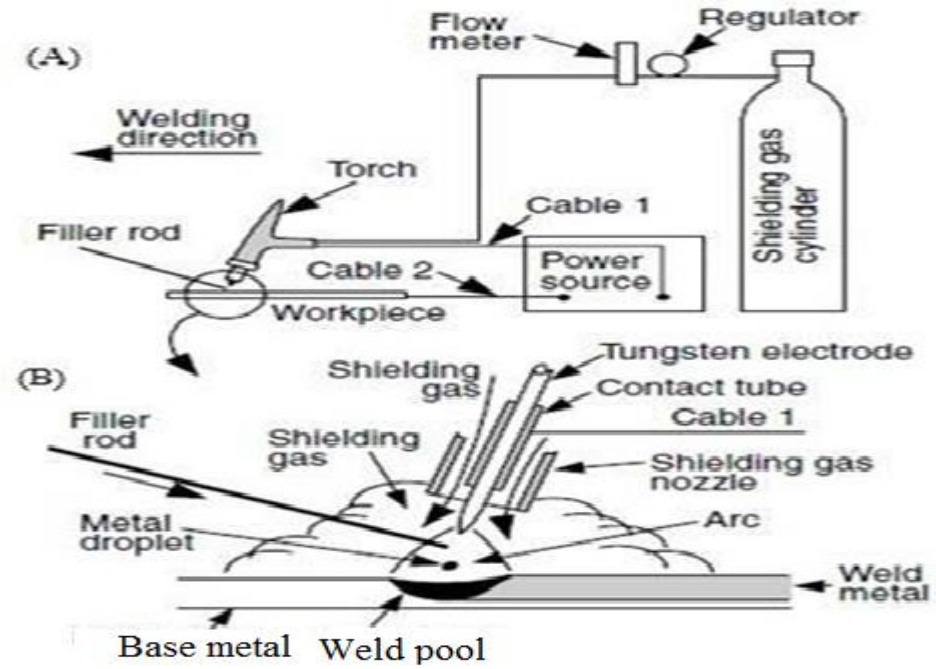


Figure 1.7 GTAW: (A) overall process, (B) welding area enlarged. [4]

1.3.2.2 Polarity

A. Direct current electrode negative (DCEN)

This, also called the straight polarity, is the most common polarity in GTAW. The electrode is connected to the negative terminal of the power supply. As shown in fig. 1.8A, electrons are emitted from the tungsten electrode and accelerated while travelling through the arc. A significant amount of energy, called the work function, is required for an electron to be emitted from the electrode. When the electron enters the work-piece, an amount of energy equivalent to the work function is released. This is why in GTAW with DCEN more power (about two-thirds) is located at the work end of the arc and less (about one-third) at the electrode end. Consequently, a relatively narrow and deep weld is produced.

B. Direct current electrode positive (DCEP)

This is also called the reverse polarity. The electrode is connected to the positive terminal of the power source. As shown in fig. 1.8B, the heating effect of electrons is now at the tungsten electrode rather than at the workpiece.

Consequently, a shallow weld is produced. Furthermore, large-diameter, water-cooled electrodes must be used in order to prevent the electrode tip from melting. The positive ions of the shielding gas bombard the workpiece, as shown in fig. 1.9, knocking off oxide films and producing a clean weld surface. Therefore, DCEP can be used for welding thin sheets of strong oxide-forming materials such as aluminums and magnesium, where deep penetration is not required. Fig. 1.8 shows three different polarities in GTAW, which are described next. [4]

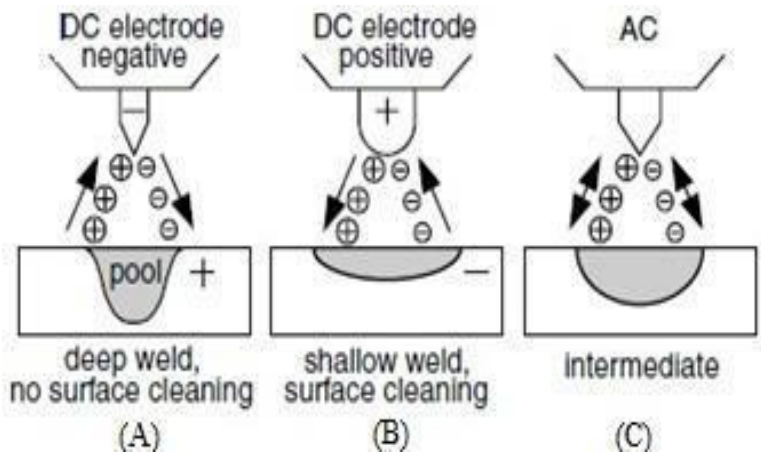


Figure 1.8 Three different polarities in GTAW [4].

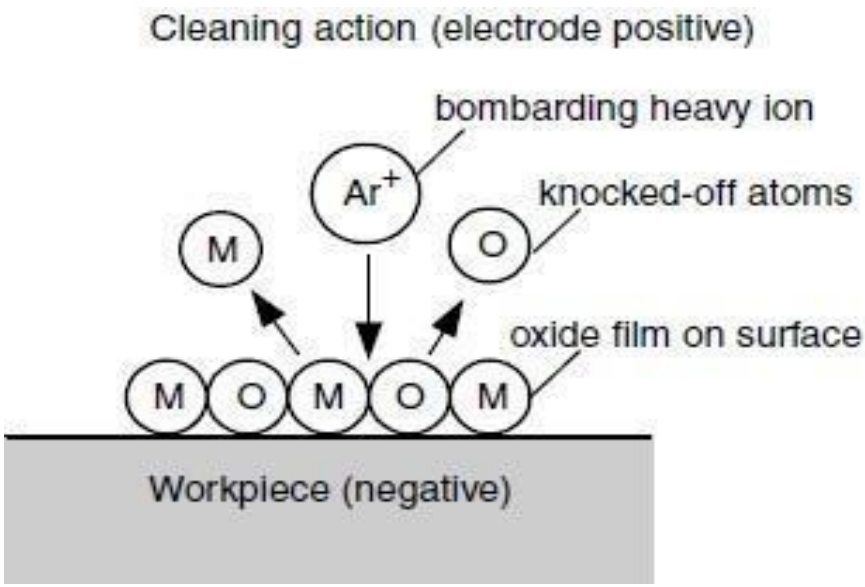


Figure 1.9 Surface cleaning action in GTAW with DC electrode positive [4].

C. Alternating current (AC)

Reasonably good penetration and oxide cleaning action can both be obtained, as illustrated in fig. 1.8C. This is often used for welding aluminum alloys.

1.3.2.3 Electrodes

Tungsten electrodes with 2% cerium or thorium have better electron emissivity, current carrying capacity, and resistance to contamination than pure tungsten electrodes. As a result, arc starting is easier and the arc is more stable. The electron emissivity refers to the ability of the electrode tip to emit electrons. A lower electron emissivity implies a higher electrode tip temperature required to emit electrons and hence a greater risk of melting the tip. [28]

1.3.2.4 Shielding Gases

In TIG welding, shielding gas plays an important role. Composition of a shielding mixture in arc welding depends mostly on the kind of material to be welded. The selection of the shielding gas should, by all means, take into account chemical-metallurgical processes between the gases and the molten pool that occur during welding. Density of the shielding gas has an important influence on the efficiency of shielding the arc and the weld pool against the ambient atmosphere. The values

indicating relative density of the shielding gas with regard to air are of primary importance. Argon and carbon dioxide are gases having by far the highest density and therefore, form an efficient gas shielding around the arc. However, the densities of hydrogen and helium are 10-20 times less than that of argon and thus, are prone to turbulent flow at the exit from the blowpipe nozzle due to thermal buoyancy. [1]

Both argon and helium can be used. Table 1.4 lists the properties of some shielding gases. As shown, the ionization potentials for argon and helium are 15.7 and 24.5 eV (electron volts), respectively. Since it is easier to ionize argon than helium, arc initiation is easier and the voltage drop across the arc is lower with argon. Also, since argon is heavier than helium, it offers more effective shielding and greater resistance to cross draft than helium. With DCEP or AC, argon also has a greater oxide cleaning action than helium. These advantages plus the lower cost of argon make it more attractive for GTAW than helium.

Table 1.4 Properties of shielding gases used for welding. [4]

Gas	Chemical Symbol	Molecular Weight (g/mol)	Specific Gravity with Respect to Air at 1 atm and 0 °C	Density (g/L)	Ionization Potential (eV)
Argon	Ar	39.95	1.38	1.784	15.7
Helium	He	4.00	0.1368	0.178	24.5
Nitrogen	N2	28.01	0.967	1.25	14.5
Oxygen	O2	32.00	1.105	1.43	13.2

Because of the greater voltage drop across a helium arc than an argon arc, however, higher power inputs and greater sensitivity to variations in the arc length can be obtained with helium. The former allows the welding of thicker sections and the use of higher welding speeds. The latter, on the other hand, allows a better control of the arc length during automatic GTAW. [4]

1.3.2.5 Advantages

1. No flux is used, hence there is no danger of flux entrapment when welding refrigerator and air conditioning components. Because of clear visibility of arc and the job, the operator can exercise a better control on welding process.
2. This process can weld in all positions and produces smooth and sound welds with less spatter.
3. TIG welding is very much suitable for high welding of thin materials (as thin as 0.125 mm).
4. It is very process for welding nonferrous metals (aluminum etc.) and stainless steel.

1.3.2.6 Disadvantages

1. Under similar applications, MIG welding is much faster process as compared to TIG welding, since it requires a separate filler rod.
2. Tungsten if it transfers to molten weld pool can contaminate the same. Tungsten inclusion is hard and brittle.
3. Filler rod ends if it by chance comes out of the inert gas shield can cause weld metal contamination.

1.3.2.7 Applications

1. Welding aluminum , magnesium, copper, nickel and there alloys, carbon, alloy or stainless steels, Inconel, high temperature and hard surfacing alloys like zirconium, titanium etc.
2. Welding of sheet metal, thinner sections, expansion bellows, transistor cases, instrument diaphragms can sealing joints.
3. Precision welding in atomic energy, aircraft, chemical and instrument industries.
4. Rocket motor chamber fabrications in launch vehicles.

Chapter 2
Literature Review

2.1 Introduction

Literature survey is the important part of any project work. A large volume of literature is available in journals and books on this particular grade i.e. AISI 304 explaining the effect of sensitization. Following are some of the literature worth mentioning to get the direction of work and relevance to a large extent.

2.2 Literature Surveyed

Rahul Unnikrishnana et al. [12] observed that steels (austenitic stainless steel) are goes to sensitization when heated to higher temperatures (400 °c to 900 °c) during the heat treatment process or certain applications (Pressure vessels) and concluded that:Shielded metal arc welding process does not result in precipitation of carbides at the highest heat input.

Eui Gyun Na et al. [13] observed that weldments treated at 730°c with 4h holding time and then coolded in the furnace are the most sensitized and concluded that:weldments that are heat treated are more sensitized than untreated weldments and parents.

Parag M. Ahmedabadi et al. [14] studied the effects sensitization on 304 stainless steel at 525°C, by using electrochemical potentiokinetic reactivation (EPR) technique and concluded that: low level of residual strain and a high fraction of annealing twins improved the resistance to sensitization.

Mohd Warikh Abd Rashid et al. [15] studied the effect of heat input on sensitization, corrosion resistance and microstructure of stainless steel by the method of XRD Analysis confirmed the presence of in stainless steel.

Pilar De Tiedra et al. [16] evaluated the degree of sensitization in resistance spot welding by the help of electrochemical potentiokinetic reactivation (EPR) test and concluded that: sensitization has combined effect on intergranular corrosion and transgranular corrosion in the heat affected zone.IDC decreases with increasing heat input because as heat input increase s, cooling rate decreases.

Effect of heat on the mechanical properties of GTA Welded AISI 304 SS joints is studied by **Subodh K. and A.Shahi**. [17] They took three heat input combinations;

low heat (2.563kj/mm), medium heat (2.784kj/mm) and high heat (3.017kj/mm). Dendrite size is smaller in low heat input than the medium and high heat inputs, so maximum tensile strength and ductility is possessed by the weld joint made using low heat input. They investigate that as heat input increases, the fusion zone and HAZ area also increase. So, extent of grain coarsening increase with increasing in heat input. The size of grains in HAZ of joints is found to be relatively coarser at high input and finer at low heat input. The authors recommend for prefer low heat input when welding AISI 304 SS using GTAW process because of the reason that at low heat input it gives better tensile strength and ductility.

P. Atanda et al. [18] investigated that SS 316L was sensitized when heated to 750- 850 °C. At 1000 °C sensitization did not occur at a soaking time of 8 hrs, there was full desensitization. The hardness of SS 316L was observed to decrease with normalization temperature.

K.H. Lo et al. [19] investigated the effects of sensitization-induced martensitic transformation on the tensile behavior of austenitic stainless steel and concluded that: Yield strength is reduced by sensitization, but ultimate tensile strength is nearly unaffected. Strain-hardening behavior is changed by sensitization too.

Maria de Jesus Perez et al. [20] evaluated the DOS of SS 304 welded by FSW and obtain the following conclusions: Sensitization was increased by heat treatment of the stainless steel at temperatures between 400°C and 850°C.The microstructure was taken by using optical microscope. The samples treated at 550°C showed the most sensitization.

V. Moura et al. [21] investigated the welded component of AISI 304L steel after 20 years of service in an oil exploitation platform working at temperatures between 773k and 873k and obtain the following conclusions: Base metal and weld metal are both sensitized, the microstructure contains intergranular Cr carbides. Carbide precipitation at relatively low temperatures.

Lima et al. [22] studied the sensitization of stainless steel AISI 304L, AISI 321, AISI 316L, and AISI 347 pipes used in refining plants. The result showed that sensitization did not occurs at temperature 380 ^{0}C but the temp. at 500^{0}C sensitization occurs for both low carbon stainless steels and AISI 347 Stainless Steel.

Wasnik et al. [23] worked on controlling grain boundary energy and make austenitic stainless steel resistant to intergranular stress corrosion cracking, two

commercial grades of ASS 316L and 304 were used in this study and found that a very high concentration of random boundaries offers an effective means of improving resistance to both IGSCC and IGC in austenitic stainless steels. This is mainly due to material is highly resistant to sensitization.

Martin et al. [24] investigated that the degree of sensitization of ASS AISI 316L and intergranular corrosion (IGC) by the help of electrolytic etching in oxalic acid and electrochemical reactivation potentiokinetic tests and concluded that: The steel annealed at temperature of 650°C have chromium-rich $M_{23}C_6$ carbides along grain boundaries

Kab et al. [25] studied the effect of sensitization in AISI 316L. Sensitized sample is investigated electrochemically by a potentio-dynamic method after solution treatment and concluded that: sensitization is increased with increasing time.

Zumelzu et al. [26] investigated the mechanical behavior of welded 316 L SS joints, the main motive was to study the behavior of welded joints considering the effect of phase change and obtain the following conclusions: The best mechanical results were obtained for weldments of 316 L SS.

Tsai et al. [27] investigated the size of the sensitization zone in SS 304 and concluded that: width of the sensitization zone is proportion to the heat input.

Ahmet et al. [28] studied the effect of shielding gas on GTAW welding of SS 316L. The mechanical properties were examined and concluded that: sample which was welded under shielding gas of 1.5%H2–Ar have highest tensile strength. With increasing hydrogen content Grain size in the weld metal increased.

Jeong et al. [29] reported that when commercial 316L stainless specimens are heat treated in single phase state at 1100^0 C, abnormal gain growth (AGG) occurs and some grains are observed to be faceted with hill and valley structures in transmission electron microscopy. When heat treated at 1300^0 C normal grain growth occurs with all grain boundaries smoothly curved. At 1200^0 C AGG occurs but there is no excessively large grain as in specimen.

Karzov and Timofeev et al. [30] had analyzed the events of failure of pipelines made of austenitic stainless steel because from the experience of operation of power generating equipments at nuclear power plant in Russia and the other countries shows that some elements of this equipment (for most part, welded joints made of austenitic stainless steels) fails during designed service life. On the basis of the analysis it was

concluded that the condition required for the initiation of inter crystalline corrosion cracking (ICCC) in austenitic stainless steels can be formulated as combined action of following three factors: the structural state of steel, chemical composition of the aqueous media and high level of stress. By changing even one of these factors, the process can be decelerated or even completely eliminated.

Kim et al. [31] studied the effect of phase's formation in AISI 316L. The crack properties and toughness characteristics in AISI 316L weld metals were investigated in different chemical composition and obtain the following conclusions: with increasing heat treatment temperature and time δ in the σ-ferrite region increased. The impact absorbed energy decreases in with increasing σ phase content.

Korinko and Malene et al. [32] had worked on the weldibility of type 304L and 316L stainless steel. Austenitic stainless steel has susceptibility to form two distinct weld defects, solidification cracking and lack of penetration, is related to chemical composition of the base and filler metal. Researchers had recommended that to help insure that types 304L and 316L SS are relatively crack insensitive and yet fully weldable, particularly when welded autogenously, limits should be placed on the Creq/Nieq ratios and sulfur content.

Raghuvir et al. [33] focused on low temperature sensitization in AISI 304LN stainless steel pipes. The specimens were taken from solution annealed pipes and welded pipes. The specimens were heated to aging at 400^0 C and 450^0 C for different durations ranging from 125 to 8000 hours and concluded that: both the base and the HAZ showed sensitization

Ramazan et al. [34] studied the mechanical properties of austenitic stainless steels welded by GMAW and GTAW. In this study, AISI 304L and 316L SS were joint by GMAW using only ER 316LSi filler metal and GTAW using ER 308L and ER 316L filler wire. Metallurgical properties of 304L and 316L austenitic stainless steel were determined. The results show that the hardness, impact and tensile strength, values of 304L and 316L stainless steels welded by GMAW are lower than that of welded by GMAW.

Shankar et al. [35] examined that during the welding of austenitic stainless steels solidification cracking is a significant problem particularly in fully austenitic and stabilized compositions. Due to low melting eutectics hot cracking occurs and concluded that nitrogen effects the weld metal cracking and microstructure.

C.J. Van Niekerk and M.du Toit [36] examined the sensitization behavior of AISI 409 stainless steel during low heat input welding. They found that due to the fast cooling rate of thick section it experience sensitization at larger heat input as compared to thin sections. They also concluded that the presence of N is harmful for Ti stabilization because N consumes Ti on cooling forming TiN thus lowering the amount of Ti available for formation of Tic. Solution treatments are carried out at 1100^0C for some specific time period followed by water quenching.

A.Yae Kina et. al. [37] examined the effect of heat treatments on transgranular corrosion resistance of AISI 347. The results reveal that Nb redistribution improved due to the solution treatment. The material shows the decrease in degree of sensitization.

At temperature below 1080^0C the microstructure of AISI 321 stainless steel appeared relatively homogenous with the average grain diameter. At temperatures equal to or higher than 1080^0C the grain growth increases rapidly. **Regina Celia De Sousa** et. al. [38] concluded that heat treated AISI 321stainless steel at 800 and 900^0C are less sensitized.

R.V.Taiwade et.al. [39] Investigated the welding behavior of AISI 304 and Cr-Mn austenitic stainless steel for single and multipass welding. Single, double and triple passes were carried out at uniform speed. Two minutes of rest time was given between the successive passes. No traces of carbides can be seen after single pass welding in both the steels. However a partial attack of carbide precipitation was observed when subjected to double pass welding. After third pass welding fully ditch sructre was observed in Cr-Mn steels wheras partially attack in 304 stainless steel. It can be seen that carbide precipitation is increasing from single to triple pass welding for both the steels.

F.F.Curiel et. al. [40] finds a new technique to improve the intergranular corrosion characteristics of 304 stainless steel. Different intensity magnetic fields was applied to check corrosion effect at the HAZ of AISI 304 stainless steel grade. They conclude that the low intensity magnetic fields increased resistance to pitting and intergranular corrosion in ss 304.

Shu Xin li et. al. [41] evaluated the effect of grain size on intergranular corrosion and chromium carbide precipitation of 316L stainless steel. They concluded that increasing grain size up to a maximum level could be an effective way to improve

the transgranular corrosion.Investigations show that the sensitization of stainless steel depends upon the nature of boundary conditions and grain size. It has also proven that the twins are not susceptible to intergranular corrosion and sensitization. So far, many plastic deformations have been used in the formation of twins to minimize sensitization. Surface mechanical attrition treatment (SMAT) is also an effective and low cost method for same.

M.Laleh and Farzad Kargar [42] studied the effect of SMAT on chromium depletion and sensitization in austenitic stainless steel. A nanostructured surface layer with a grain size about 10 nm was fabricated on AISI 304 austenitic stainless steel using SMAT. The SMATed samples shows such a low DOS value which can be considered as non-sensitized material. This can be mainly due to the existence of twin boundaries in the microstructure which are not susceptible to carbide precipitation because of their regular and coherent atomic structure and extremely low grain boundary energy.

To improve penetration characteristics of SS 304, small amounts of O_2, and H_2 gas are added into the argon torch shielding gas. Weld depth is lowest when pure argon is used. In order to improve the weld depth penetration**, R.I.Hsieh** et. al. [43] added 1%O_2 and 5%H_2 in the Argon gas. By adding O_2 the soluble oxygen content in the weld pool is increased which improves weld penetration. Because of its high thermal conductivity the addition of hydrogen also improve penetration and gives a larger heat input. Hydrogen effects on weld width as compared to depth, however it increases the penetration but results in wider weld**.**

Ahmet Durgutlu [44] also investigates the effect of Argon as a shielding gas during GTAW welding of austenitic stainless steel. He concludes that penetration depth and weld bead width increases with the increase in hydrogen content. The grain size in weld metal also increase with increasing hydrogen content.

2.3 Research Gap

No. of researchers had done a lot of work on SS 304 using different welding processes like shielded metal arc welding, gas metal arc welding, gas tungsten arc welding but it is observed that no systematic work on the effect of welding heat input and normalizing time and temperature conditions on the mechanical and metallurgical properties of welded specimens had been reported. Literature survey also reveals that there is a scope of working in this direction because of the critical applications (like in nuclear industry, chemical industry etc.) of this material and to make it safer for further use.

2.4 Objectives

Following objectives has been derived from the literature survey.

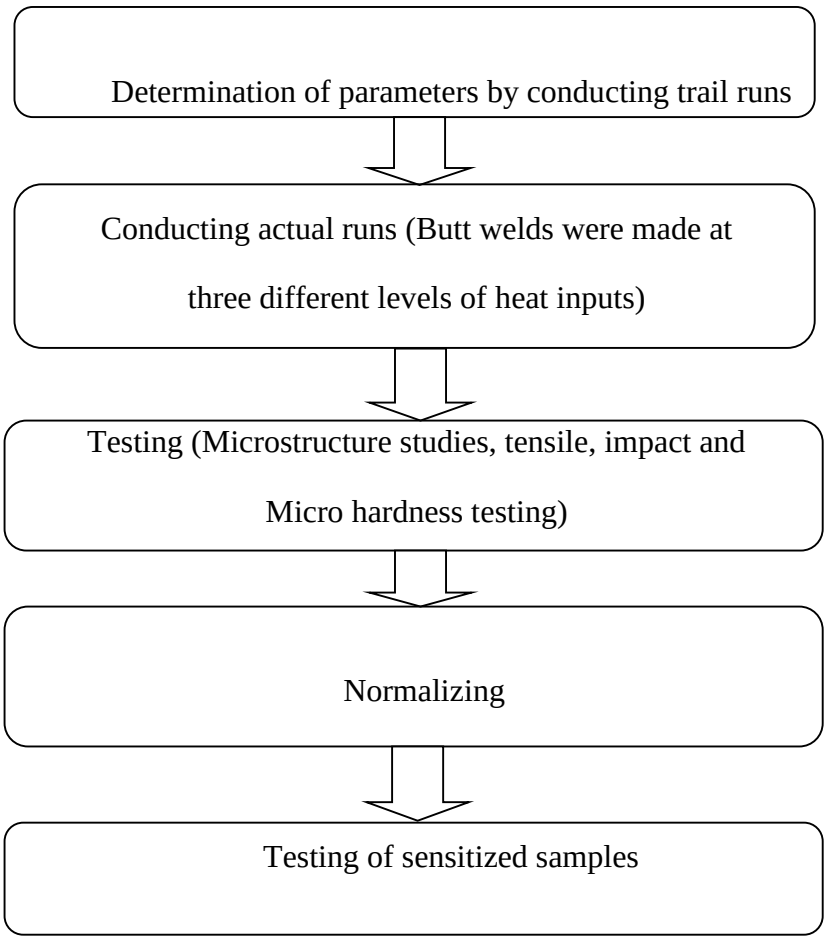
1. To study the effect of welding heat input on performance of GTAW butt welded SS 304 specimens by varying heat input conditions.
2. To find the effect of sensitization conditions on mechanical and microstructural properties of butt welded specimens, thereby studying the sensitization behavior of SS 304.

Chapter 3
Experimentation and Testing

This chapter discusses the detail about the experimental data, base metal, filler metal, and welding procedure, welding parameters, heat treatment of welded specimen and testing.

3.1 Plan of Experimentation

Experimentation was conducted in two phases, in the first phase SS 304 plates were butt welded at three different levels of heat inputs to find out the best suited welding parameter in terms of mechanical and metallurgical properties. In the second phase, the best results achieved were further used for Sensitization studies.



Flow chart shows how experimentation was conducted.

3.2 Base Metal and Filler Metal

The plates of SS 304 stainless steel of 5 mm in thickness was selected to study the effect of welding heat input and sensitization on the performance of GTAW butt welded specimens. SS 304 filler metal of 1.6 mm diameter was used. Table 3.1 shows the chemical composition of base metal used.

Table 3.1 Chemical composition (wt. %) of base metal.

C	Mn	P	S	Si	Ni	Cr	Mo	Fe
.07	1.4	.02	.02	.4	10	18.1	1.7	

3.3 Welding Equipment

GTAW was used for experimentation. Welding machine used is shown in fig. 3.2, having following specifications.

- Manufacturer : Tech Pro, India
- Supply voltage : 380/415/440 V
- Welding current range : 5 A –350 A (DC)
- Open circuit voltage : 80 V
- Weight : 280 kg

Figure 3.2 Welding machine used.

3.4 Welding Consumables and Variables

- Material thickness : 5 mm
- Joint design : Double V

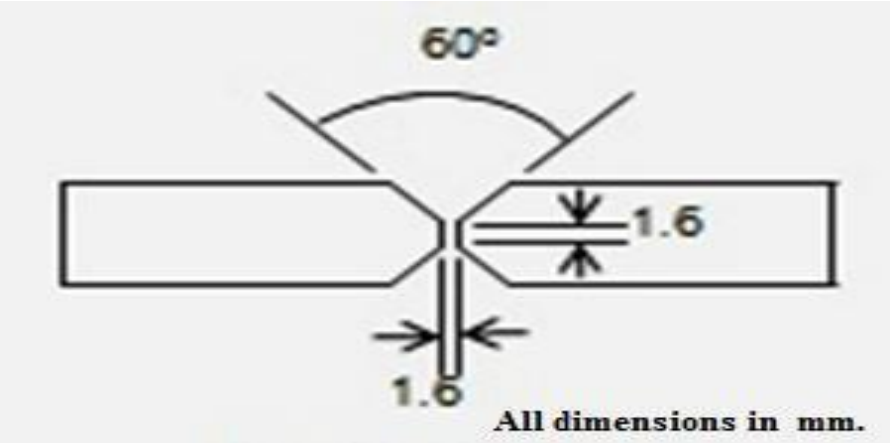


Figure 3.3 Joint design used, Double V.

- Root face : 1.6 mm
- Root gap : 1.6 mm
- Joint type : Butt joint
- No. of Passes : 2
- Gas Flow rate : 10 lpm
- Electrode dia : 1.6 mm
- Electrode type : EW-TH-2 (Thoriated tungsten)
- Filler rod dia : 1.6 mm
- Filler metal : SS 304
- Shielding gas : Industrial Argon
- Machine make : Tech Pro
- Polarity : Straight
- Welding torch used : Air cooled
- Voltage = 25 V
- Welding current = 130, 170 and 210 A

3.5 Working Procedure

Test coupons were prepared by butt welding 304 austenitic stainless steel specimens to each other by using a welding wire made from the same material. GTAW manual welding process was used. First of all, trial runs were conducted to find out the current range to be used and three set of TIG parametric combinations were decided for various heat inputs 130 A, 170 A and 210 A, because of well-established fact that among all the welding variables in arc welding processes welding current is the most influential variable since it affects the current density and thus the melting rate of the filler as well as the base material. The heat input from the welding process plays a major role in the heating and cooling cycles experienced by the weld and parent plate during welding. For a given plate thickness, a high heat input is likely to result in a slower cooling rate than a low heat input, and will therefore produce a softer microstructure in the HAZ that is less prone to hydrogen cracking. However, that does not mean that welding should always be carried out with a high heat input, because this brings with it other problems, such as loss of mechanical properties and an increased risk of solidification cracking. So it is necessary to select a heat input to give a sound weld with the desired mechanical properties.

Welding heat input 'Q' was calculated as:

$$Q = (K \text{ x } V \text{ x } I \text{ x } 60)/ (\text{Sx}1000)\ kj/mm$$

Where V is arc Voltage, I is welding current, and S is welding speed in mm/min. Thermal efficiency factors k was considered 0.7. The value derived from this formula may be multiplied by a factor k, the thermal efficiency factor for the welding process.

Table 3.2 shows the heat input at different welding conditions and fig. 3.4 shows the pictures of samples welded at different heat inputs. Mechanical and microstructural properties of the samples were examined. Detail description of the welding Procedure adopted is given on next few pages and fig. 3.5 shows the procedure followed for welding.

Table 3.2 Heat input at different welding Conditions**.**

Welding current (A)	Voltage (V)	Pass	Welding Speed mm/min	Heat input per unit length per pass (kJ/mm)	Total heat input per unit length of weld (kJ/mm)
130	25	1st	95	1.43	3.32
		2nd	72	1.89	
170	25	1st	105	1.7	3.8
		2nd	85	2.1	
210	25	1st	215	1.02	2.20
		2nd	187	1.18	

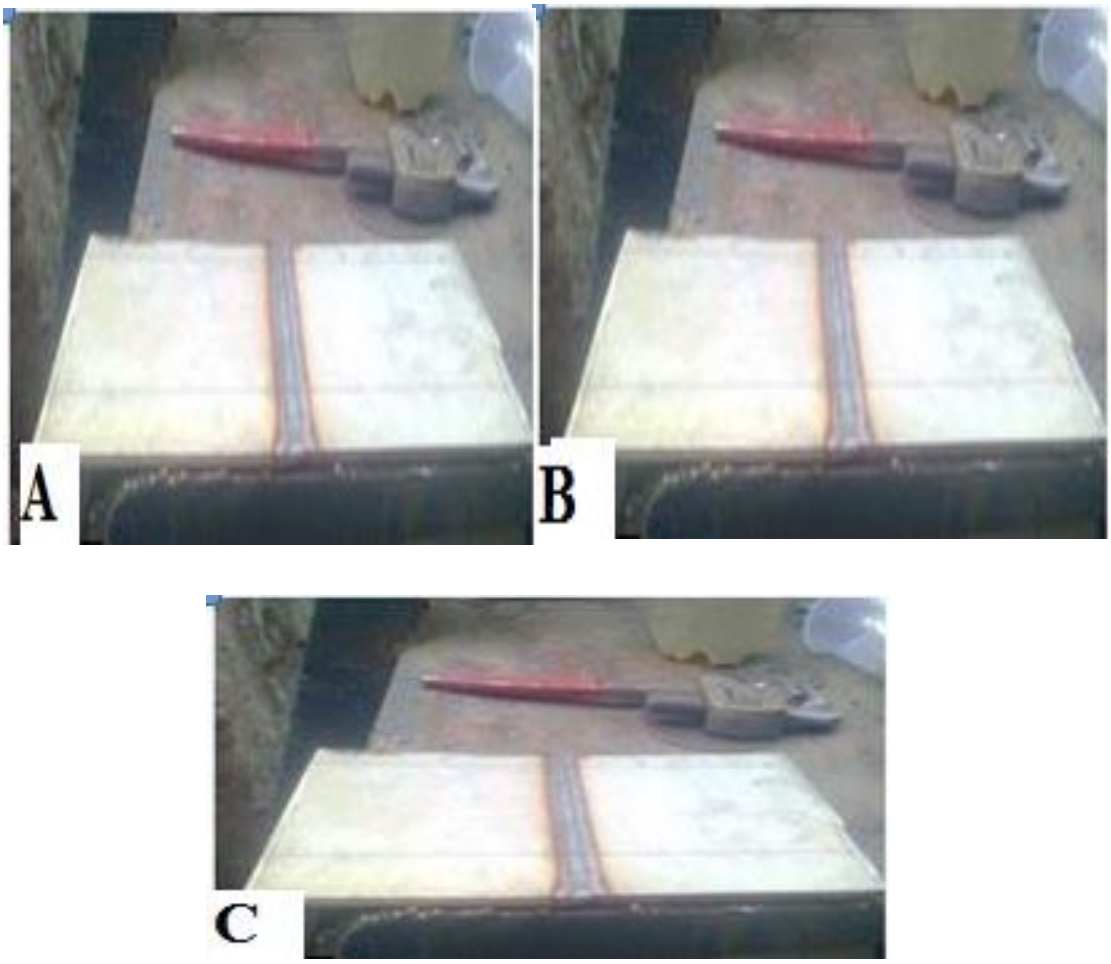
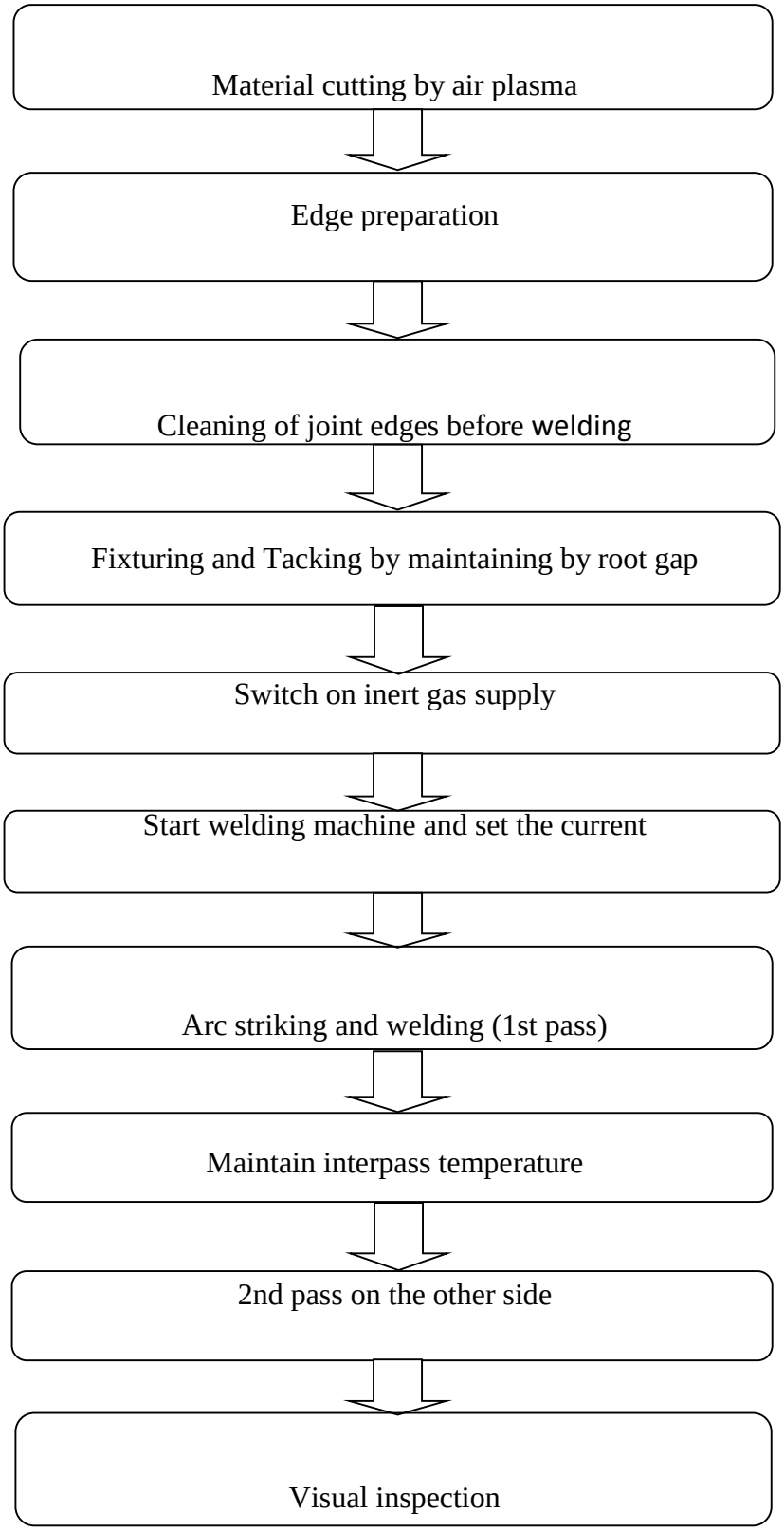


Figure 3.4 Photographs of samples welded at different heat input conditions. (A) 3.32 kJ/mm, (B) 3.8 kJ/mm, (C) 2.20 kJ/mm



Procedural steps for welding.

All the work of experimentation was done in the premises of Pratap engineering works Pvt. Ltd. Ludhiana. Firstly, specimen of SS 304, 125 mm long, 125 mm wide and 5 mm thick were cut by plasma cutter. Double V joint design was used so that welding could be accomplished in two numbers of passes ensuring full penetration by maintaining root face of 1.6 mm and bevel angle of 60^0, fig. 3.6 shows the photograph taken during edge preparation by grinder. Current of the machine was set to the desired value. Before starting welding, joint edges and two or three inches of adjacent surfaces were cleaned chemically in order to avoid contamination like rust, scale, dust, oil, moisture etc. Plates to be welded were clamped by C clamps and tacked having root opening of 1.6 mm because joints not fixed in fixture must be tack welded to maintain a uniform gap and alignment along the entire length. The tacks should be placed in sequence to minimize the effect of shrinkage. In fitting two sheets, tack welds should be placed at each ended the middle section. Fig. 3.6 (A) and (B) show how the sheets close up when tack welding progresses from one end.

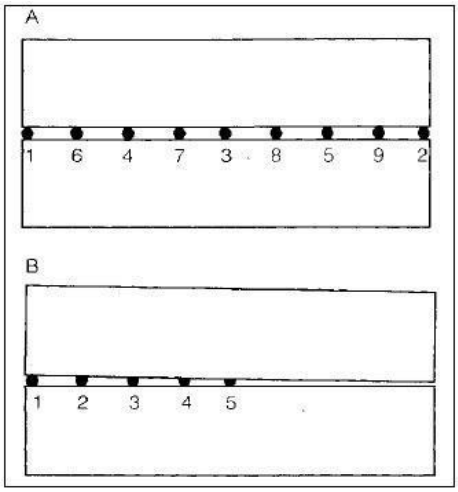


Figure 3.6 Tack welds sequence. The correct tack weld sequence is shown in A above.

Gas supply was turned on before starting the arc because gas pre-flow is must for good quality welding, as it removes air from the torch and gas hose and ensures complete and prefect shielding of the electrode and base metal even before the arc is stuck and during arc striking and gas flow rate was also set to desired value i.e. 10 lt/min. The welding is started by moving the torch along the joint and arc time was recorded carefully for the calculation of welding speed and heat input. After welding, samples were cooled in the air and prior of giving the second pass on the other side of the plate an interpass temperature between 150 –175^0C was maintained, fig. 3.8 shows

the photograph of sample before laying second pass. Same procedure was adopted for making the second pass on the other side. During and after welding the joints were visually inspected for their quality and it was ensured that all weld beads possessed good geometrical consistency and were free from visible defects like surface porosity, blow holes etc. Fig. 3.7 shows the plates in the as welded condition using different heat inputs.

Figure 3.7 Photograph of the sample prior to 2nd pass.

3.6 Testing

Microstructural studies, tensile strength, micro hardness and impact strength tests were performed on as welded and sensitized specimens. Firstly, testing was done on as welded samples to find out the welding parameters for further work on sensitization studies and further testing was carried out on sensitized (heat treated) specimens welded at parameters decided after testing of as welded samples.

3.6.1 Specimen Sampling

In order to evaluate the mechanical and microstructural properties of the SS 304 weldments, the specimens for transverse tensile testing, impact strength, micro hardness testing and micro structural studies were machined out from welded pads.

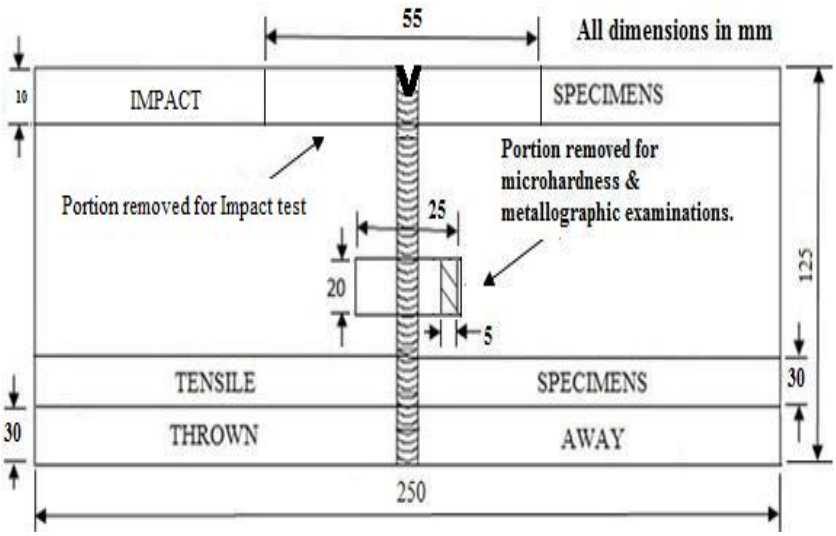


Figure 3.8 Illustration of weld samples for the tests.

3.6.2 Tensile Test

It is also called tension test and is used to determine tensile strength of the material when subjected under uniaxial loading. By pulling something, it will be very quickly determined how the material will react of forces being applied in tension. Tensile test helps in determining tensile and yield strength of material.

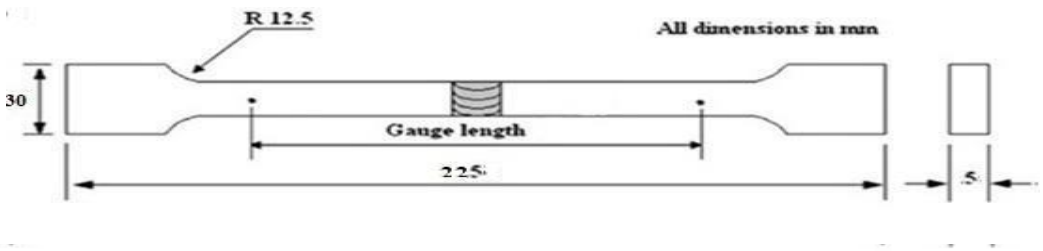


Figure 3.9 Dimensions of the tensile specimen.

Specimens for tensile were taken as perpendicular to weld direction. Tensile tests were conducted at R&D Centre, Ludhiana, in accordance with IS 1608:2005. (Metallic materials - Tensile testing at ambient temperature.) Speed of tensile testing was 8 mm/min. The specimens were tested on FIE make Universal Testing Machine, UTE-60, shown in fig. 3.10, it is an electronic type, hydraulically controlled digital tensile testing machine of 600 /KN capacity. Fig. 3.11 shows the location of fracture of the as welded samples.

Figure 3.10 Universal testing machine, UTE-60.

Figure 3.11 Photograph of base metal and as welded tensile tested specimens showing location of fracture.

3.6.3 Microhardness Measurements

The term microhardness tests usually refer to static indentation made with loads not exceeding 1 kgf. The surface being tested generally requires a metallographic finish; the smaller the load, the higher the surface finish is required. The procedure for microhardness testing is very similar to that of the standard Vickers hardness, except that it is done on a microscopic scale with higher precision instruments. Microhardness measurements were carried out across the HAZ using Vickers hardness testing machine shown in fig. 3.12 in accordance with IS 1501:2002 (Method for Vickers hardness test for metallic materials) at CTR, Ludhiana.

Figure. 3.12 Vickers hardness testing machine.

3.6.4 Microstructural Examination

In order to determine the microstructural changes taking place during welding under different heat input conditions and normalizing, microstructural examination was carried out on the cross section of the base metal, fusion boundary including both HAZ and weld metal and micrographs were captured with the help of optical microscope attached with a camera. Microstructural examinations were performed at LPU.

Figure 3.13 Optical microstructure

3.6.5 Impact strength Examination

Impact strength, is the capability of material to withstand a suddenly load and it is expressed in terms of energy. Impact strength examinations were performed at LPU SOM Lab.

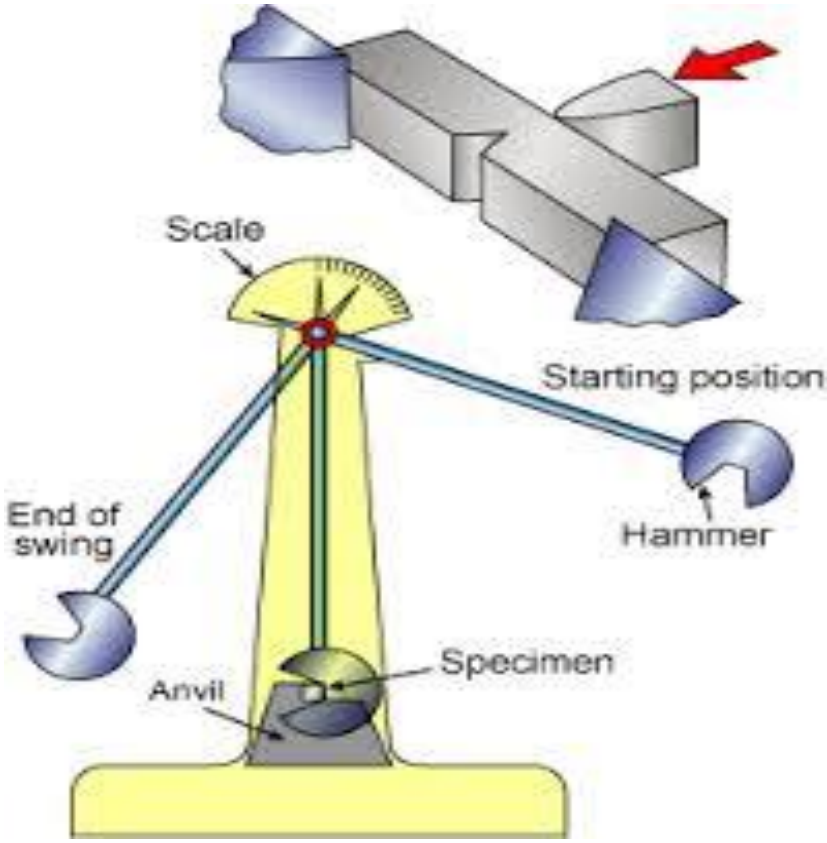


Figure 3.14 charpy impact test machine.

3.7 Sensitization Treatments

Performance of the samples welded at lowest heat input 2.2 kJ/mm (210 A) was found to be the best when tensile strength, impact strength, micro hardness, microstructure were compared among the welded samples (welded under different heat input conditions) and base metal. Therefore, 210 A current was selected for sensitization studies and one more test coupon of SS 304, 250 mm long, 500 mm wide and 5 mm thick was prepared by using same parameters and procedure as mentioned in section 3.5. Fig. 3.14 shows the plates welded for sensitization studies.

Figure 3.15. Photograph showing the base plates in welded condition for sensitization studies.

Nine set of samples for mechanical and microstructural studies were extracted from the welded plate and sensitized by performing the normalized heat treatment by varying the temperature and soaking time. Temperatures used were 750^0C, 850^0C and 1000^0C. The different soaking times at these temperatures were 30 minutes, 60 minutes, and 120 minutes. Samples were sensitized at six different time and temperature combinations.

- 750^0 C for 30 minutes
- 750^0 C for 60 minutes
- 750^0 C for 120 minutes
- 850^0 C for 30 minutes
- 850^0 C for 60 minutes
- 850^0 C for 120 minutes
- 1000^0 C for 30 minutes
- 1000^0 C for 60 minutes
- 1000^0 C for 120 minutes

Heat treatment was done in muffle furnace installed in metallurgy lab of our college. Fig. 3.16 shows the pictures taken during heat treatment.

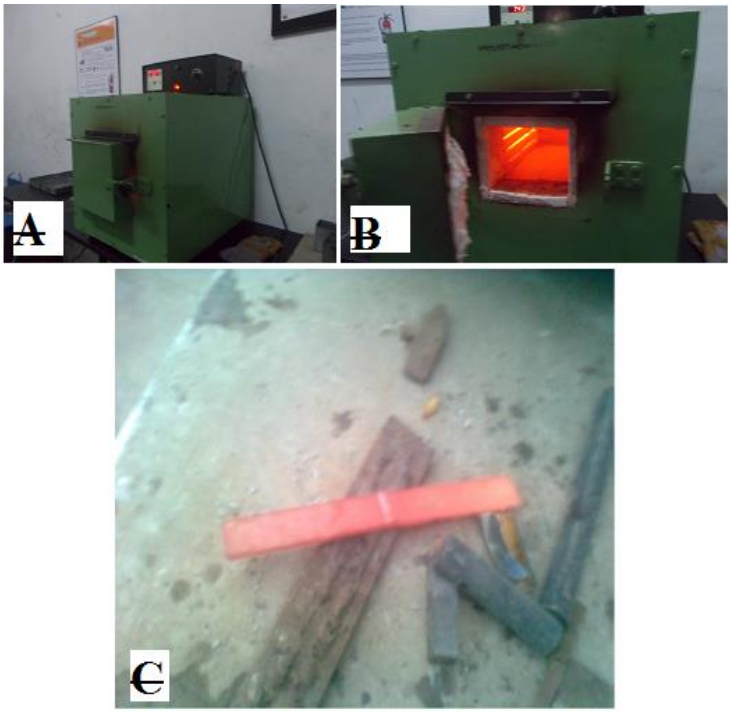


Figure 3.16. Photographs of heat treatment. (A and B) Muffle furnace used for normalizing, (C) Tensile specimen taken out of the furnace and allowed to cool in air.

All the 12 specimens (9 tensile specimens + 9 specimens for microstructure and microhardness+9 specimens for impact) extracted from a plate welded at 210 A were normalized by heated at above mention temperature and time followed by cooling in still air. For example : 3 specimens (1 tensile specimen + 1 microstructure and micro hardness +1 impact) were heated at 750^0 C for 30 minutes and then air cooled and 3 specimens (1 tensile specimen + 1 specimen for microstructure and micro hardness +1 impact) were heated at 750^0 C for 60 minutes and cooled in air and so on.

3.7.1 Testing after Sensitization

After normalizing samples were subject to same tests which were performed on as welded samples those were tensile test, micro hardness and microstructure examination and impact test fig. 3.17 (a) shows the fractured sensitized tensile specimens, (b) shows the impact specimens, (c) shows the hardness and microstructure specimens Detail about the testing procedure adopted and equipment used during testing was already mentioned in section 3.5.

Figure 3.17. (a) Specimens after sensitization and tensile test. **(b)** Specimens after impact test. **(c)** Specimens after hardness and microstructure test.

Chapter 4
Results and Discussions

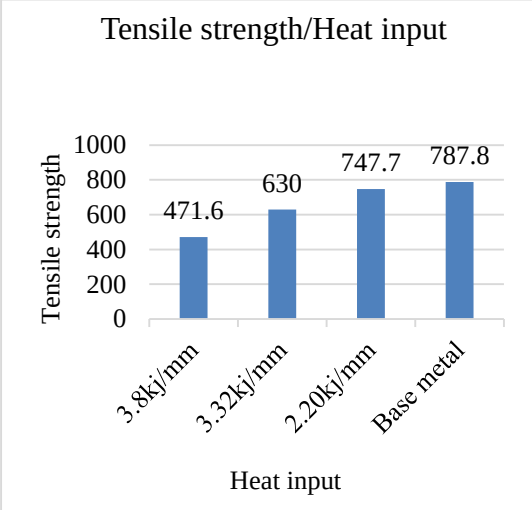
Table 4.1 shows the experimental results of mechanical testing.

Table 4.1 Experimental results

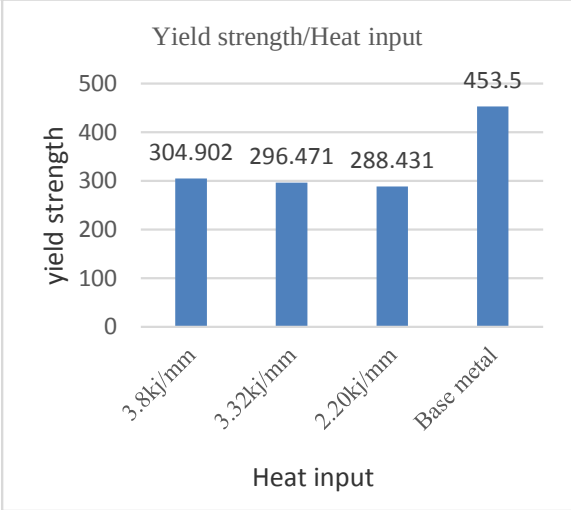
Description	Tensile Strength MPa	Yield Strength MPa	Micro hardness HV		Impact strength J/mm^2
			Weld zone	HAZ	
Base Metal	787.40	453.5	253		1.6
2.2 kJ/mm (210A)	747.70	288.431	250	250	1.56
3.8 kJ/mm (170A)	471.60	304.902	250	250	1.48
3.32 kJ/mm (130A)	630.00	296.471	240	240	1.4
750° C for 30 min.	732.13	443.48	246	247	1.4
750° C for 1 hour.	750.780	477.023	235	237	1.28
750° C for 2 hour.	736.76	497.196	232	234	1.2
850° C for 30 min.	736.711	463.56	234	261	2.6
850° C for 1 hour.	742.63	452.63	260	243	2.5
850° C for 2 hour.	722.04	462.15	242	232	1.9
1000° C for 30 min.	685.93	431.25	235	225	1.84
1000° C for 1 hour.	616.88	376.52	227	226	2.0
1000° C for 2 hour.	629.61	371.03	225	235	2.2

4.1 Butt Welds

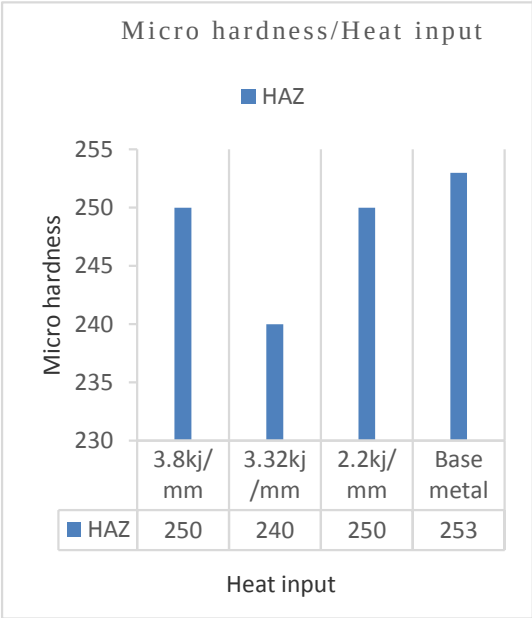
Fig. 4.1 and 4.2 Shows the graphs (mechanical properties) and photomicrographs of as welded specimens and base metal. All the welds have good joint strength, Specimen welded at 130,170 and 210 are fractured within the weld bead. Lack of fusion was also absorbed in weld made at 130 a, when it was polished. Highest tensile strength is found at lowest heat input of 2.2 kJ/mm, it is about 94.28 % of the base metal. Hardness is maximum at lowest heat input 2.2 kJ/mm and minimum in sample welded at 130 A because arc formed by using this current was quite weak. Impact strength is maximum at lowest heat input



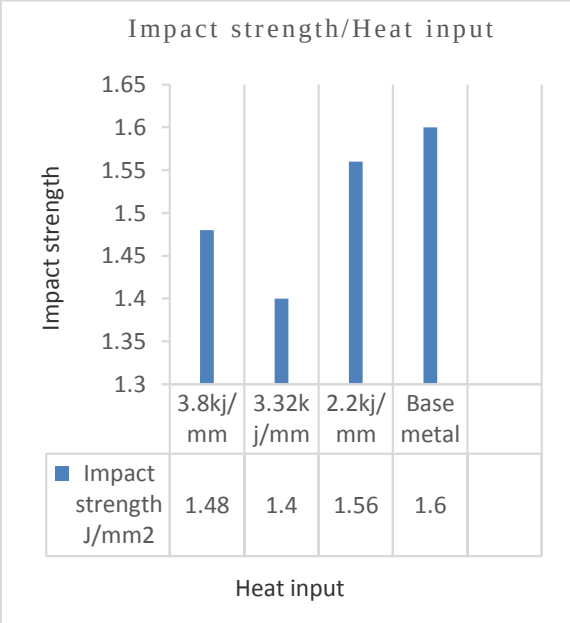
(A)



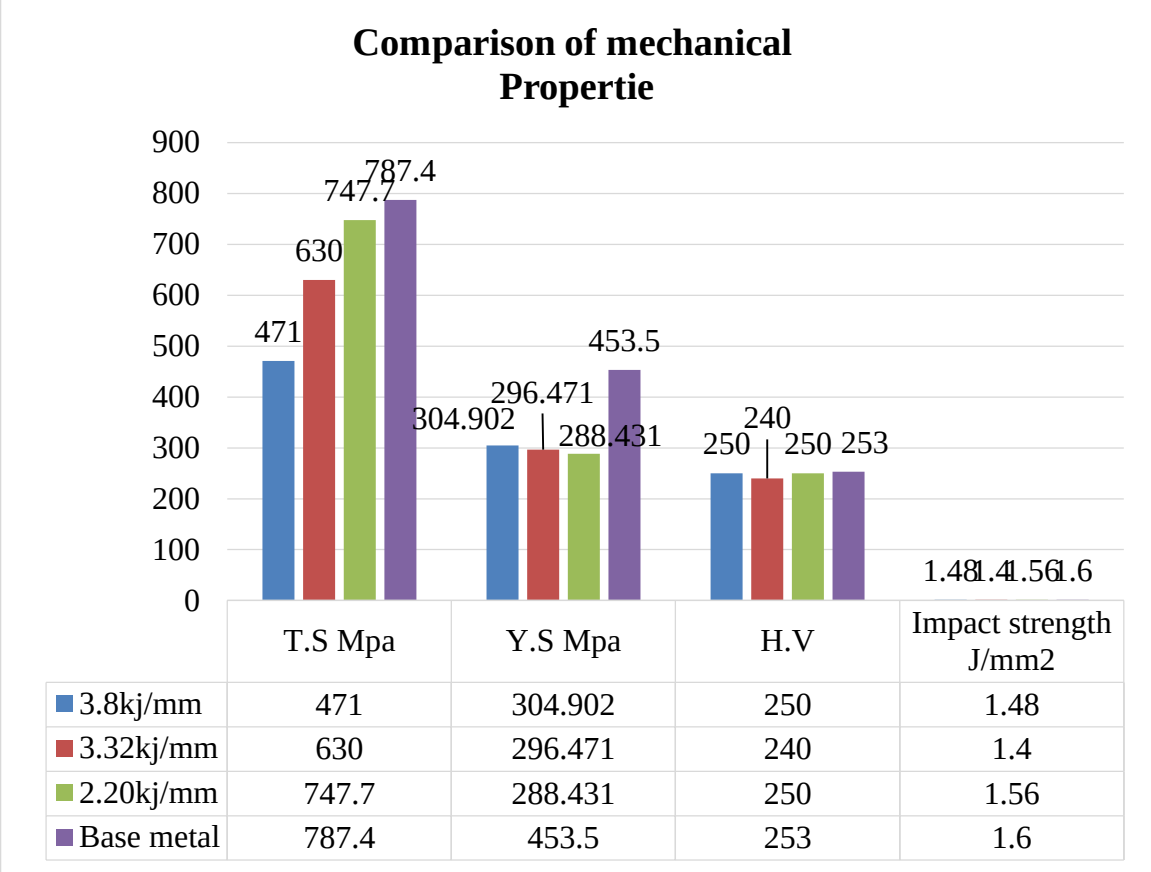
(B)



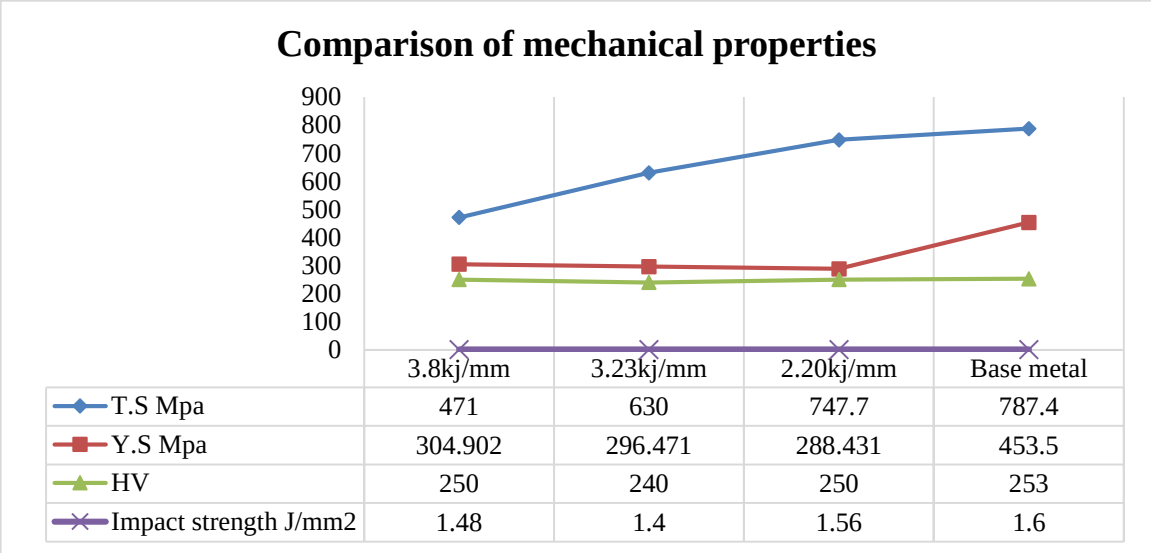
(C)



(D)



(E)



(F)

Figure 4.1. Mechanical properties of as welded samples V/S heat input. (A) Tensile strength, (B) yield strength, (C) micorhardness, (D) Impact strength (E) comparison of mech. Properties and (F) comparison of mech. properties on line chat for better understanding.

The microstructure of weld metal shows delta ferrite in the matrix of austenite and of parent metal shows equiaxed grains of austenite. Dark streaks visible are stringers of ferrite and these are minimum in sample welded at minimum heat input of 2.20 kJ/mm.

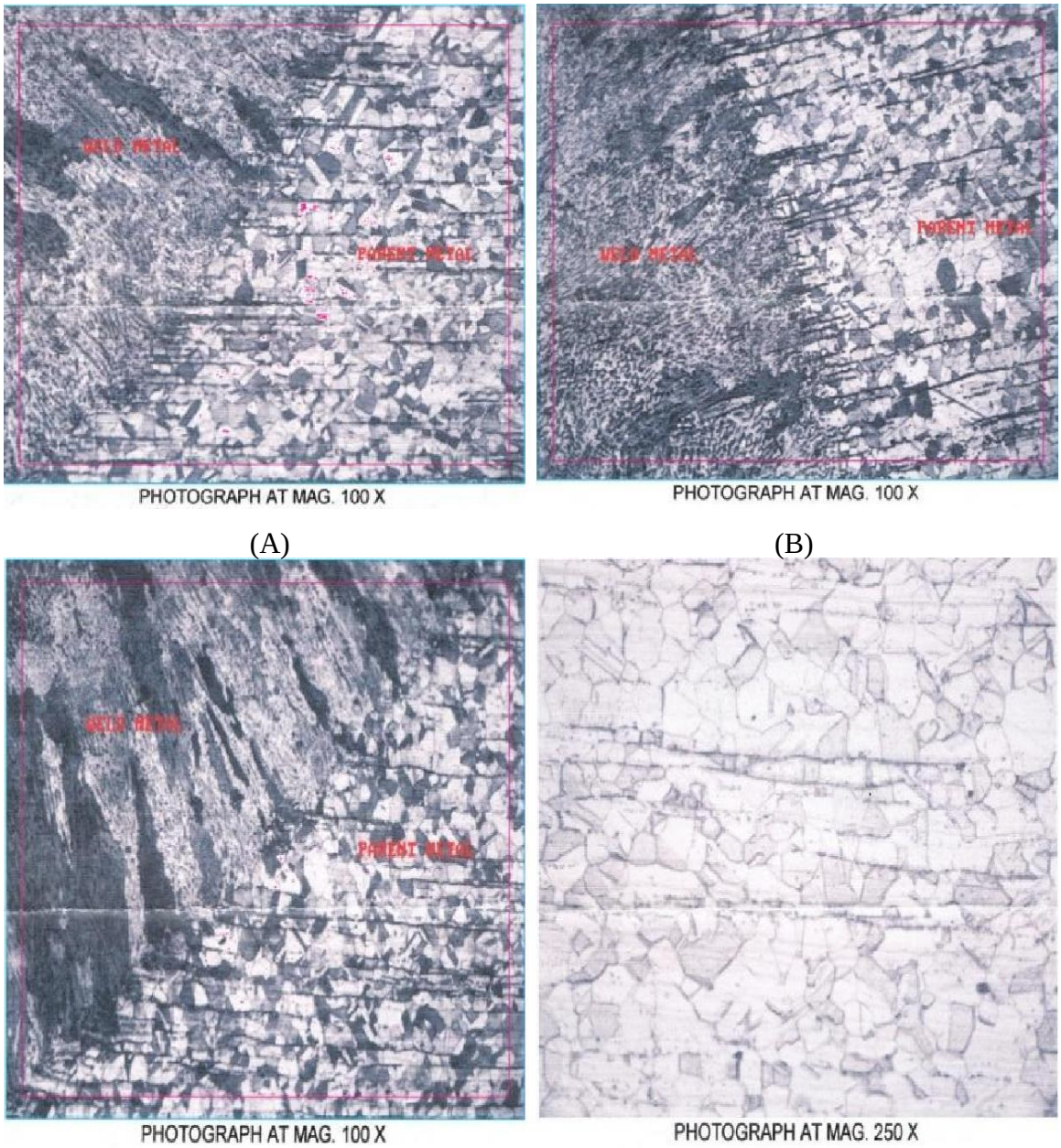
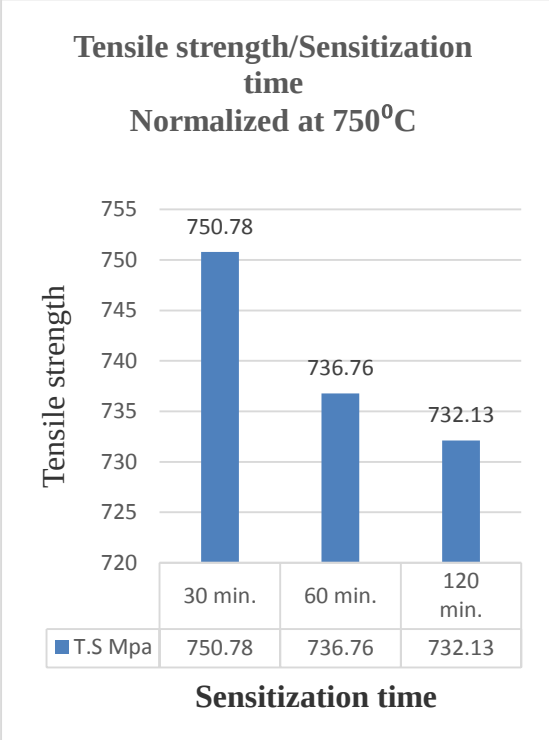


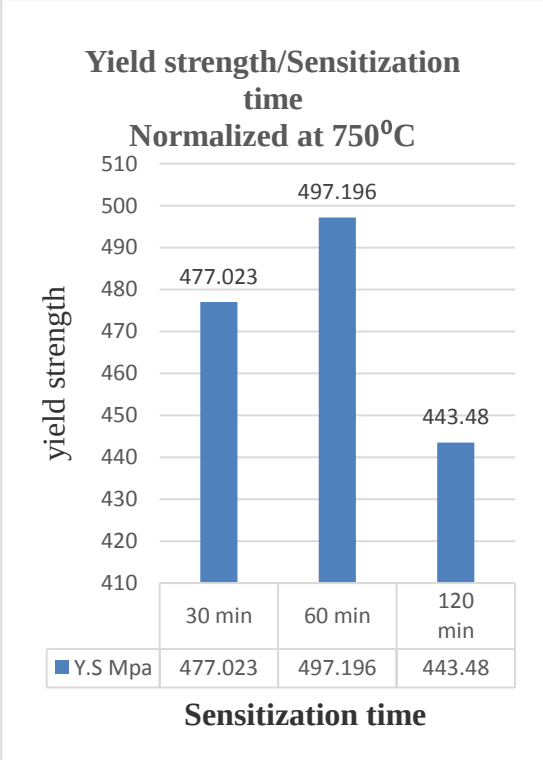
Figure 4.2 Photomicrographs of base metal and as welded specimens, welded under different heat conditions (A) 2.2kJ/mm, (B) 3.32kJ/mm, (C) 3.8 kJ/mm and (D) Base metal.

4.2 Normalizing at 750^{0}C

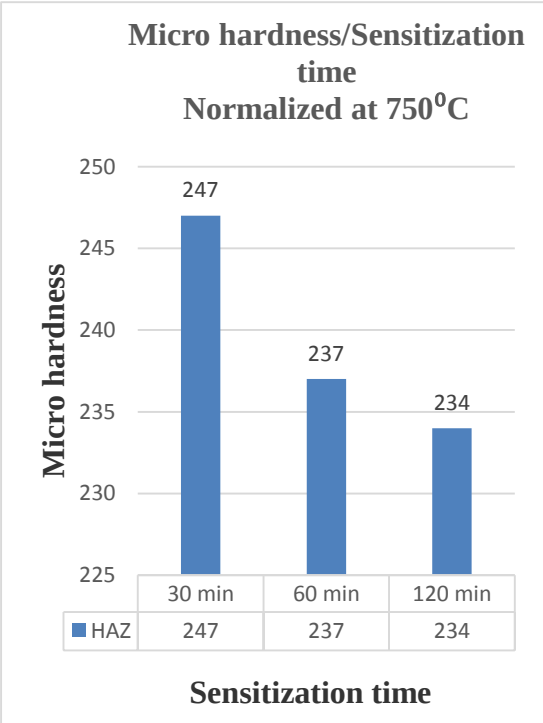
Mechanical properties and photomicrographs of samples normalized at 750^{0}C are shown in fig. 4.3 and 4.4. Tensile strength, microhardness and impact strength had decreased when temperature and normalizing time increased.



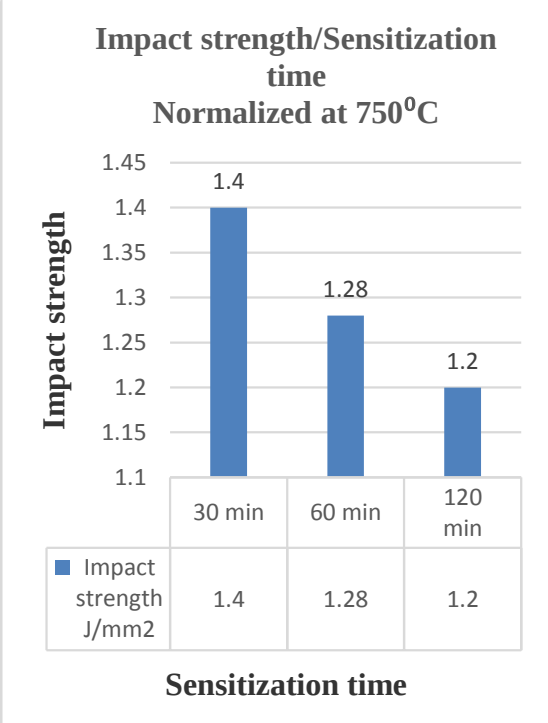
(A)



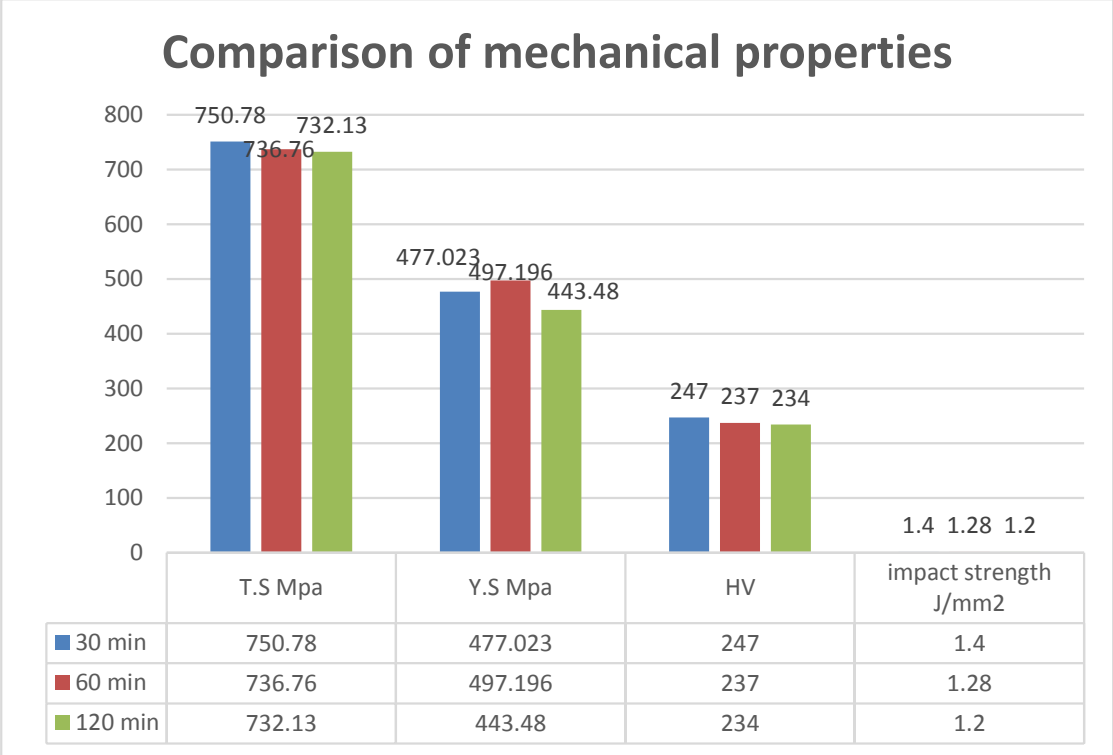
(B)



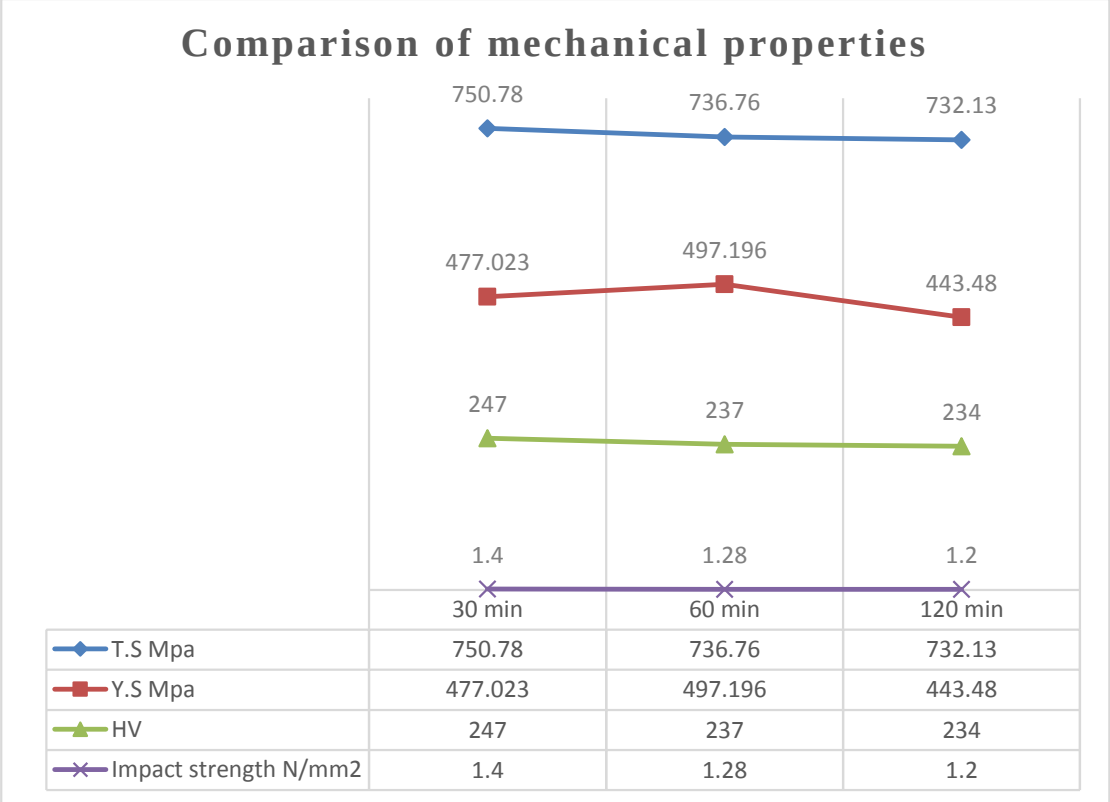
(C)



(D)



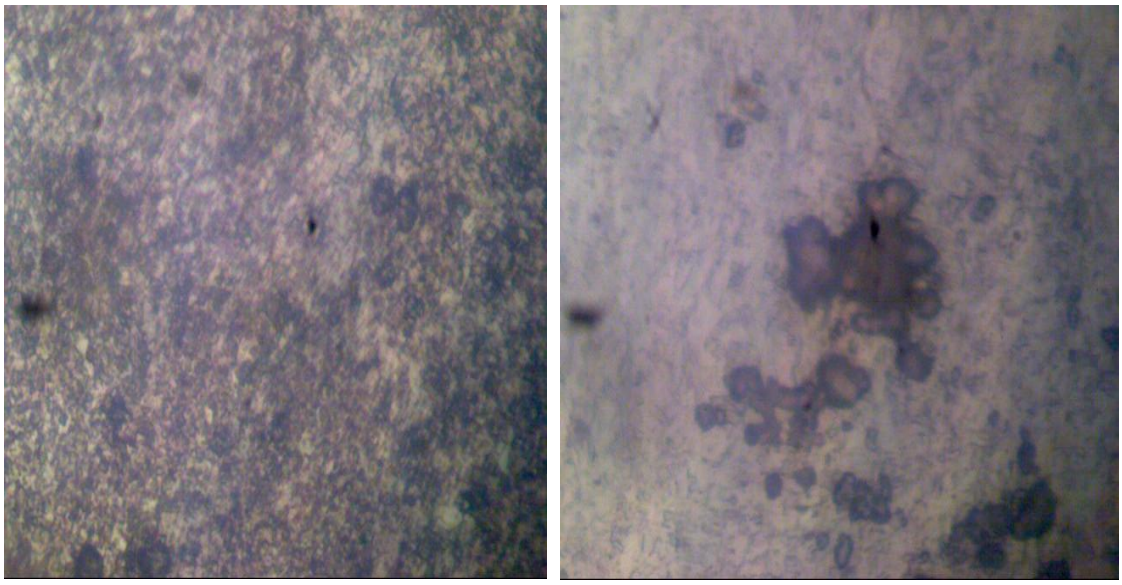
(E)



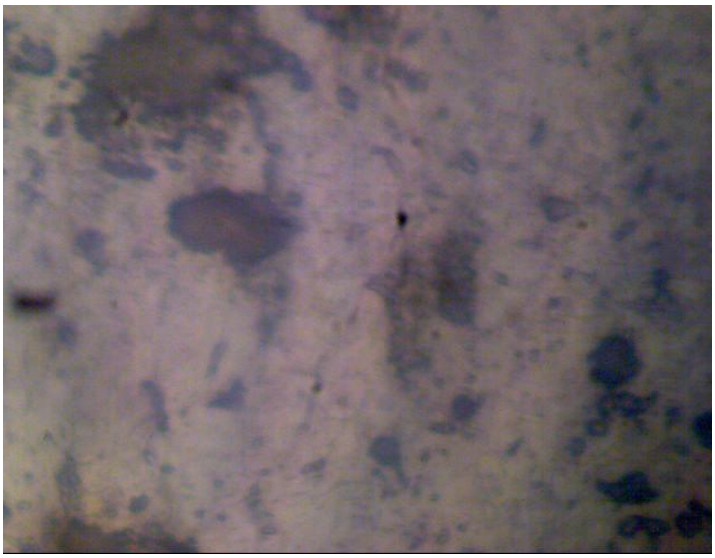
(F)

Figure 4.3. (A-F) Mechanical properties of normalized specimens heated to 750^{0}C held for 30 minutes, 60 minutes and 120 minutes.

Grain coarsening had taken place when samples were held for 120 minutes and tensile strength had decreased due to the same, black streaks of ferrite had increased with increase in exposure time. Carbide precipitates could be seen in samples soaked for 60 and 120 minutes but absent in sample soaked for 30 minutes.



(A) (B)

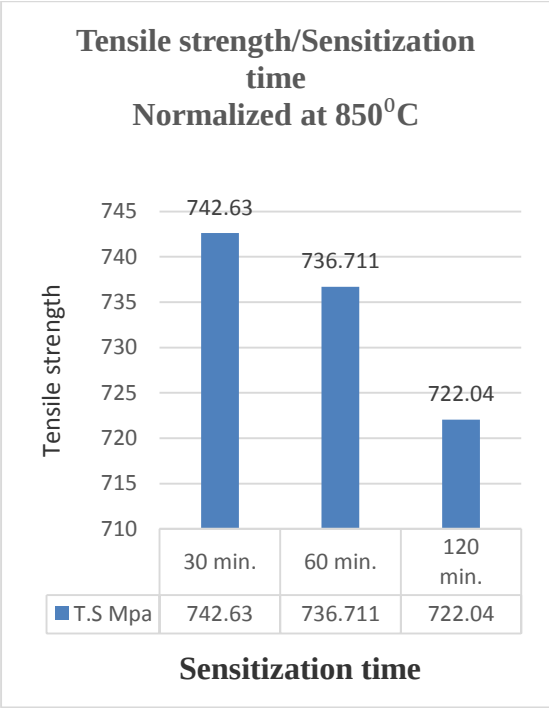


(C)

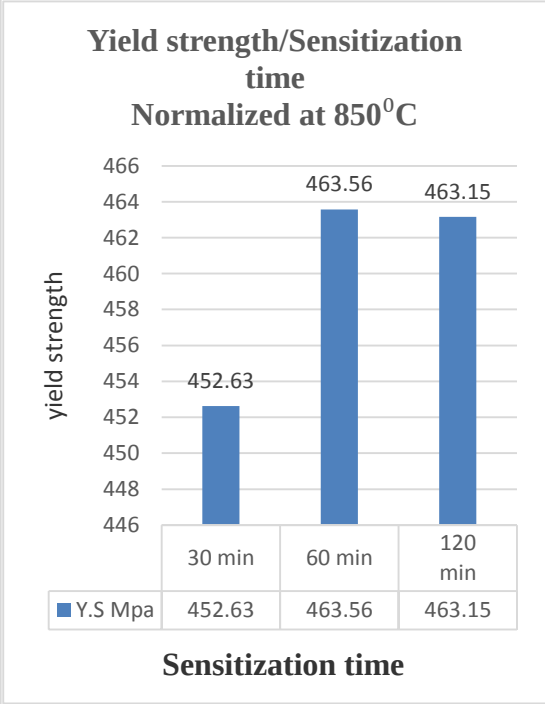
Figure 4.4. The optical microstructures of the specimens heat-treated at 750^{0}C for (A) 30 minutes, (B) 60 minutes and (C) 120 minutes.

4.3 Normalizing at 850^{0}C

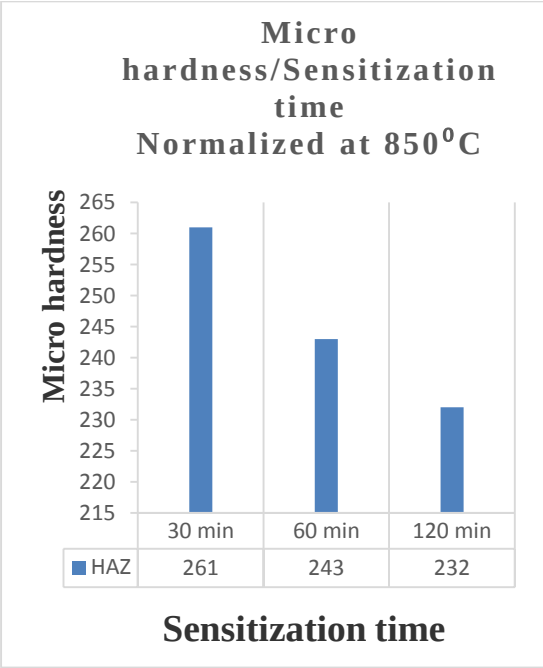
Pattern followed by mechanical properties of samples sensitized at 850^{0}C resembles with the samples sensitized at 750^{0}C. Tensile strength, microhardness and impact strength had decreased when temperature and normalizing time is increased. Yield strength had increased with increase in exposure time.



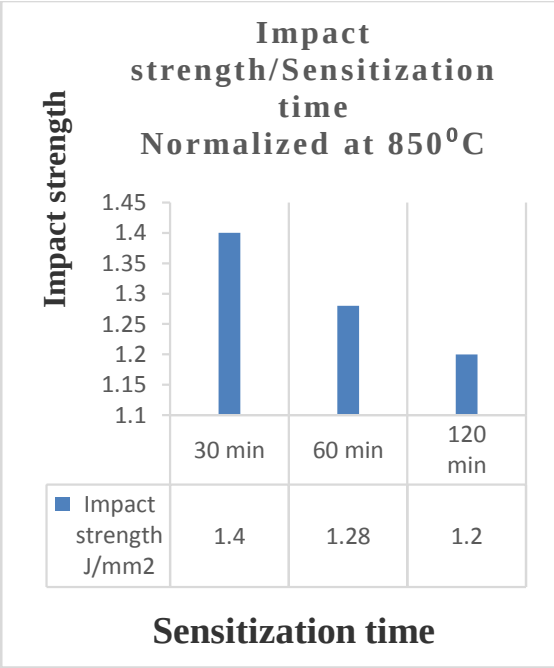
(A)



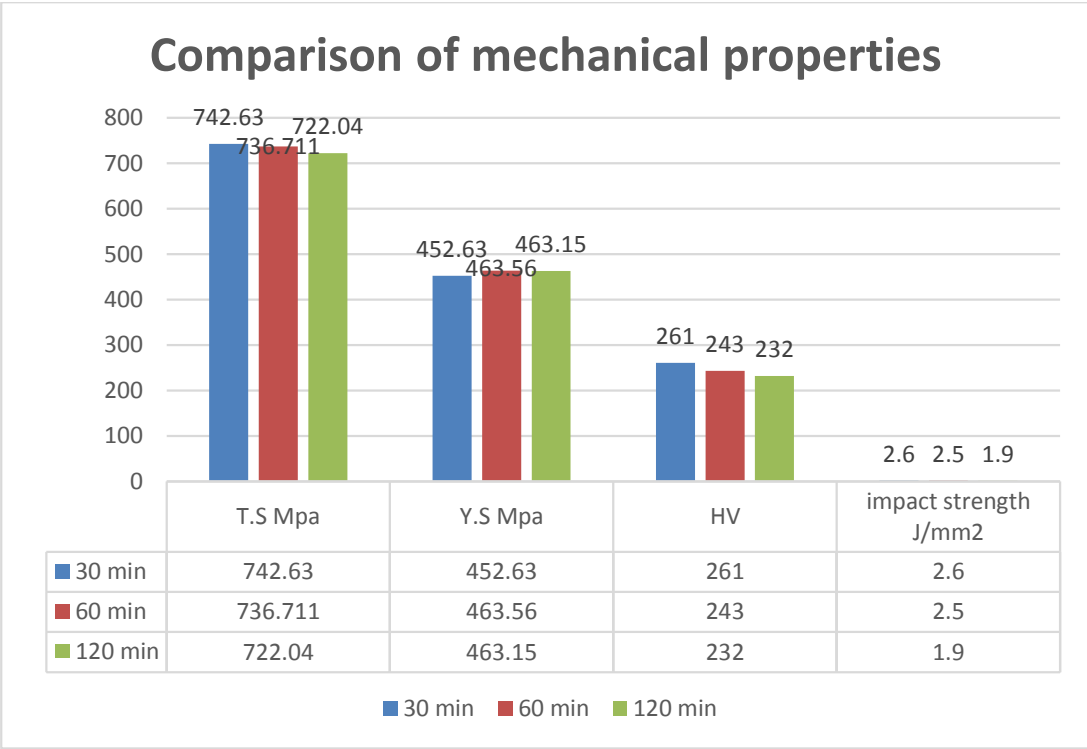
(B)



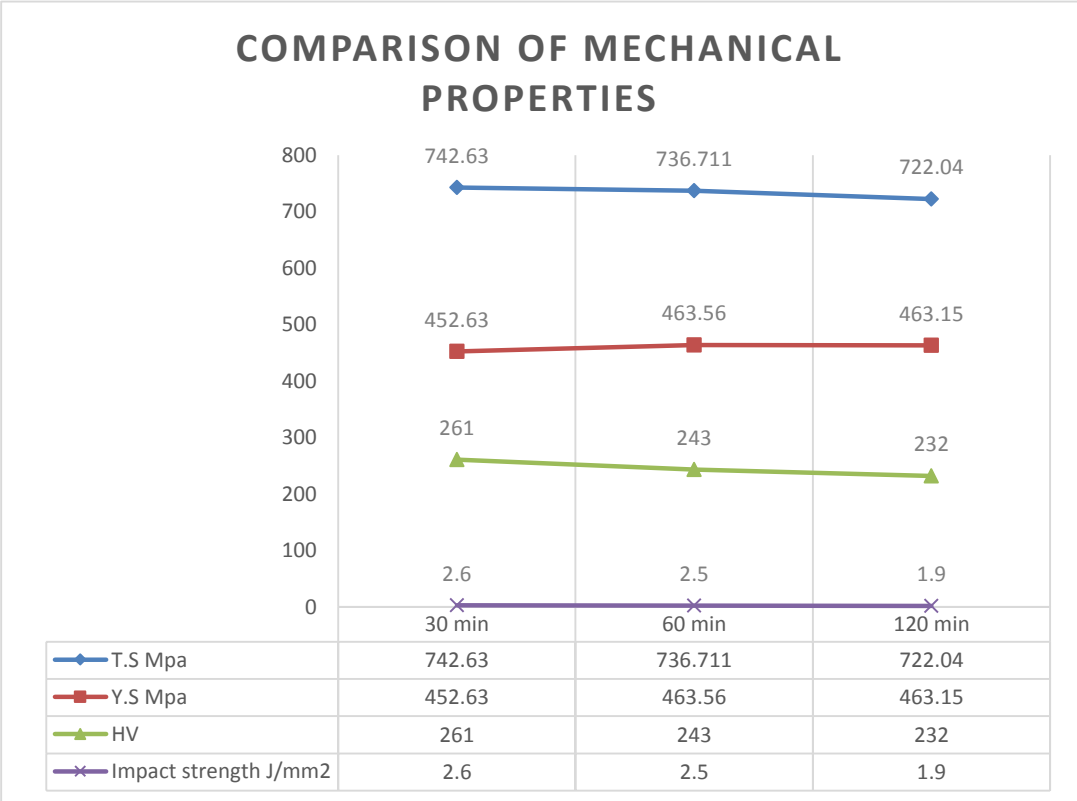
(C)



(D)



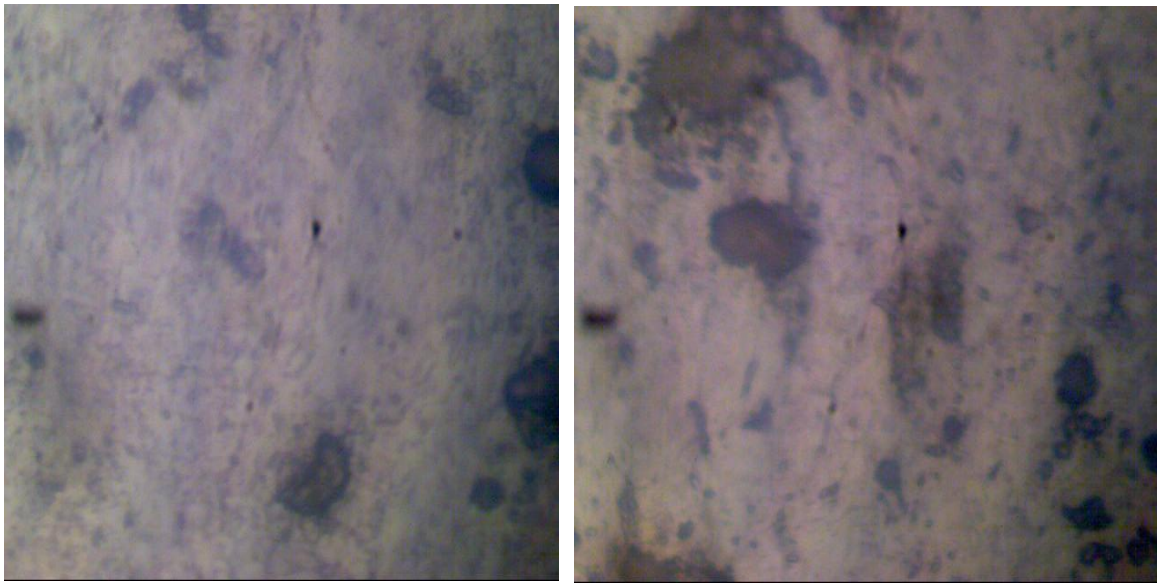
(E)



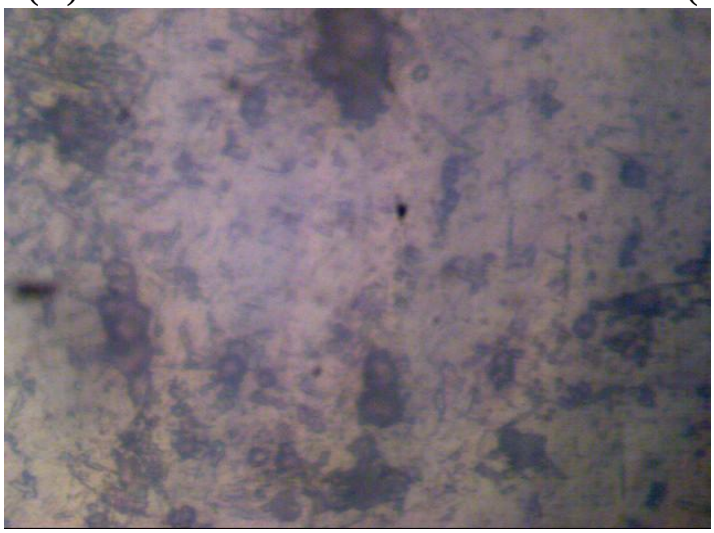
(F)

Figure 4.5. (A-F) Mechanical properties of normalized specimens heated to 850^{0}C held for 30 minutes, 60 minutes and 120 minutes.

Fig. 4.6 shows the optical microstructures of specimens heat-treated at 850^0C. Carbide precipitates could be seen here but negligible in sample soaked for 30 minutes and maximum in sample soaked for 120 minutes, black spots in at the grain boundaries are chromium carbides and are very clearly visible in fig. 4.6 (C).



(A) (B)

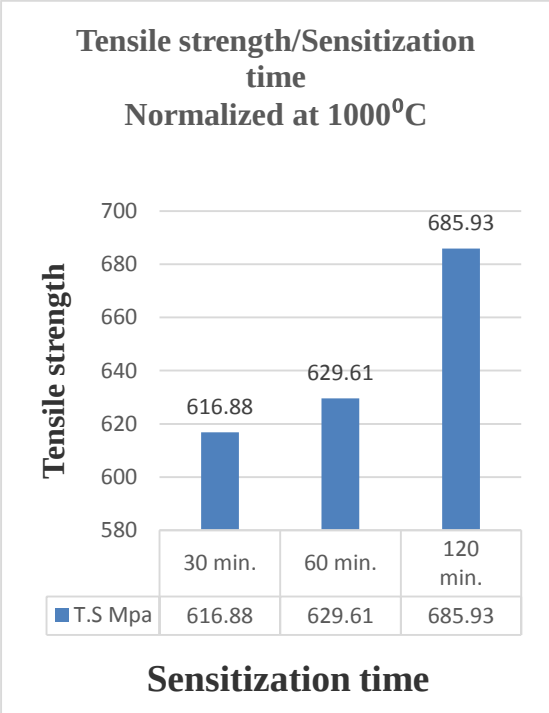


(C)

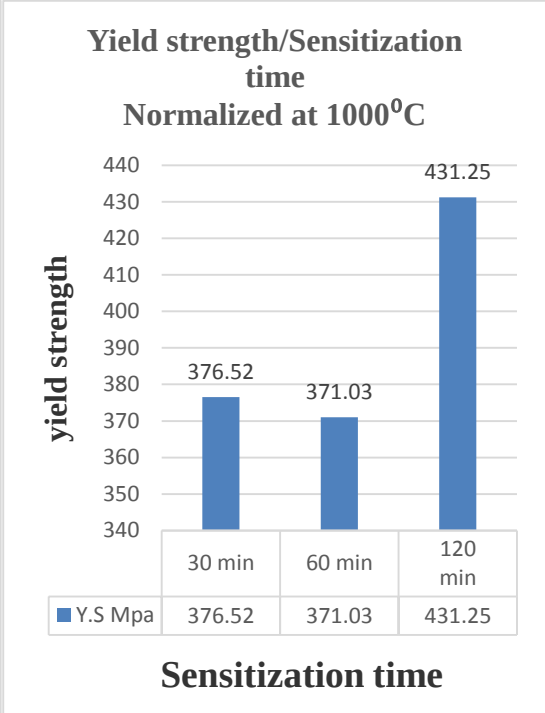
Figure 4.6. The optical microstructures of the specimens heat-treated at 850^0C for (A) 30 minutes, (B) 60 minutes and (C) 120 minutes.

4.4 Normalizing at 1000^{0}C

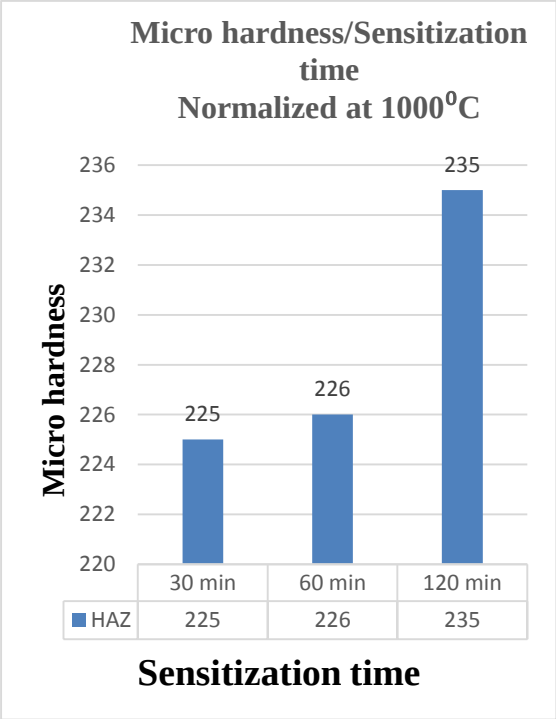
Mechanical properties and photomicrographs of samples normalized at 1000^{0}C are shown in fig. 4.7 and 4.8 Tensile strength, microhardness and impact strength had decreased when temperature and normalizing time is increased.



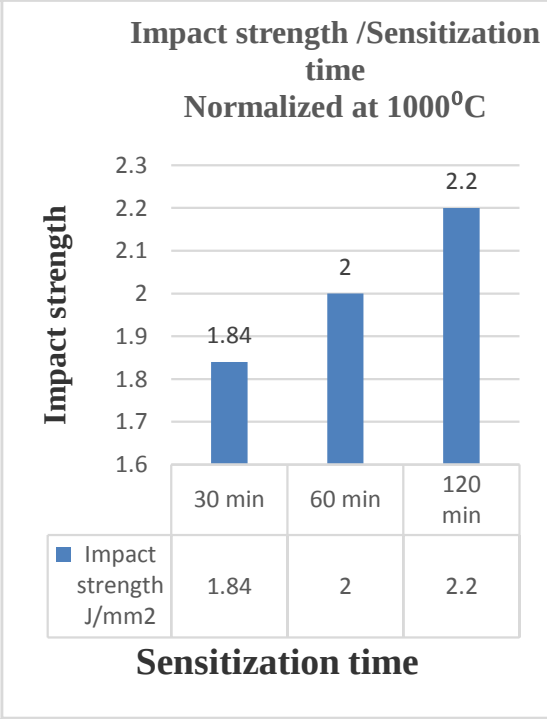
(A)



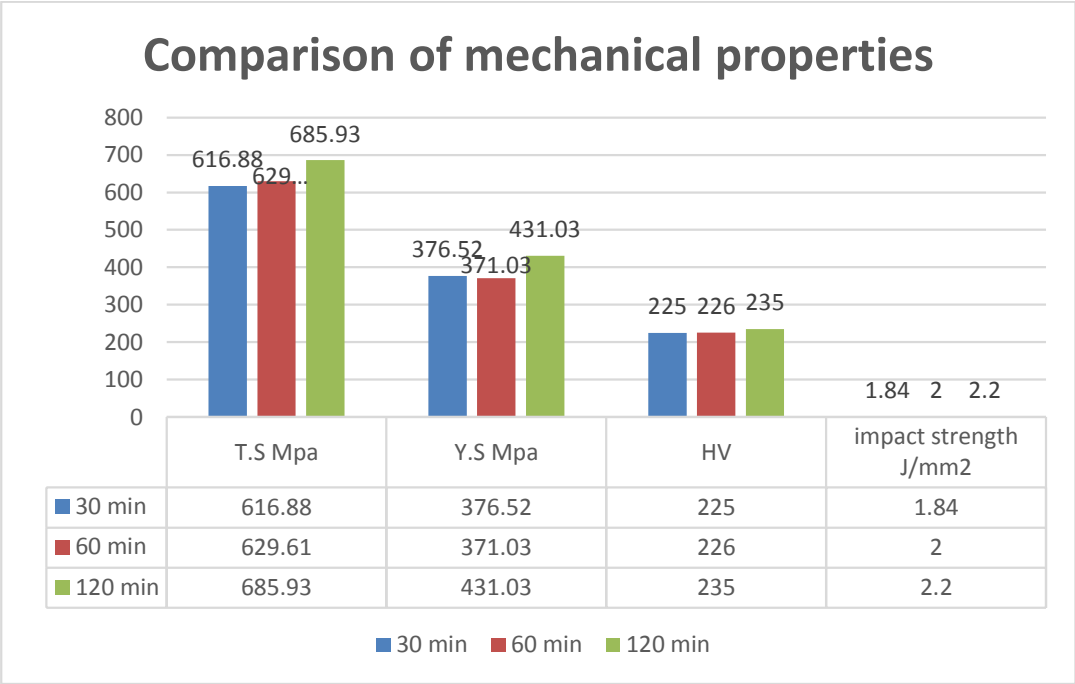
(B)



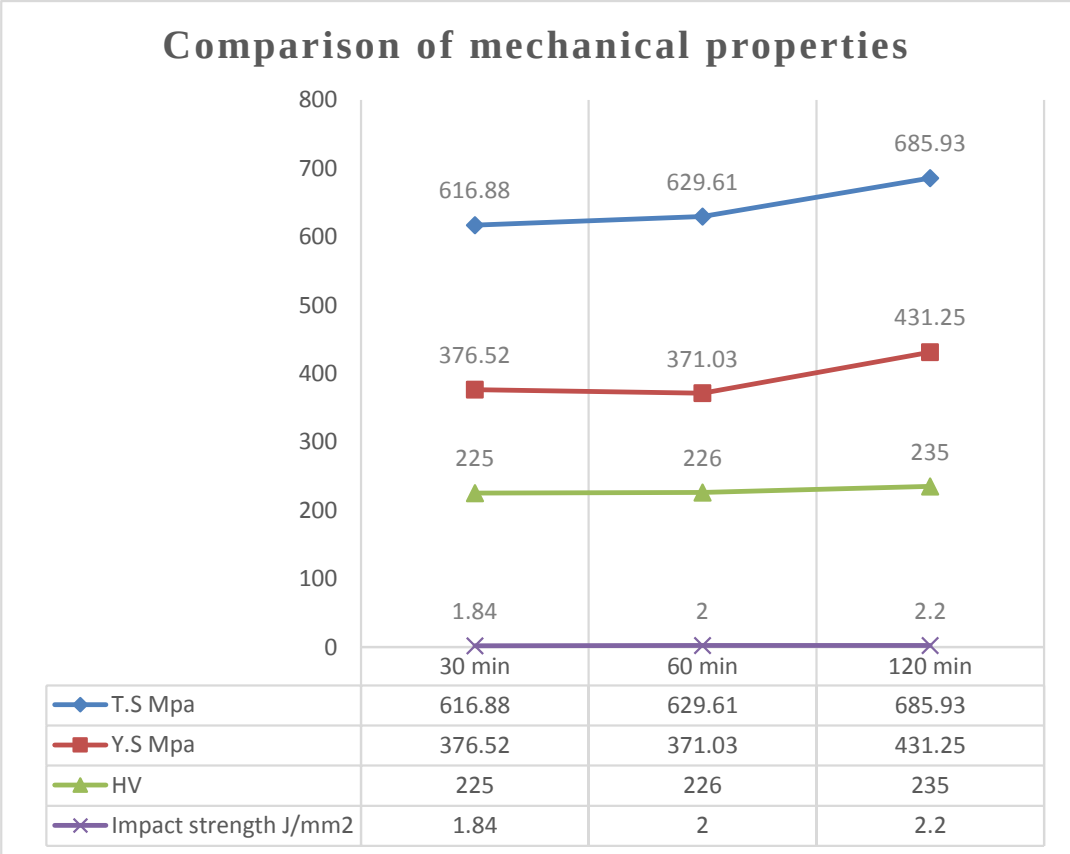
(C)



(D)



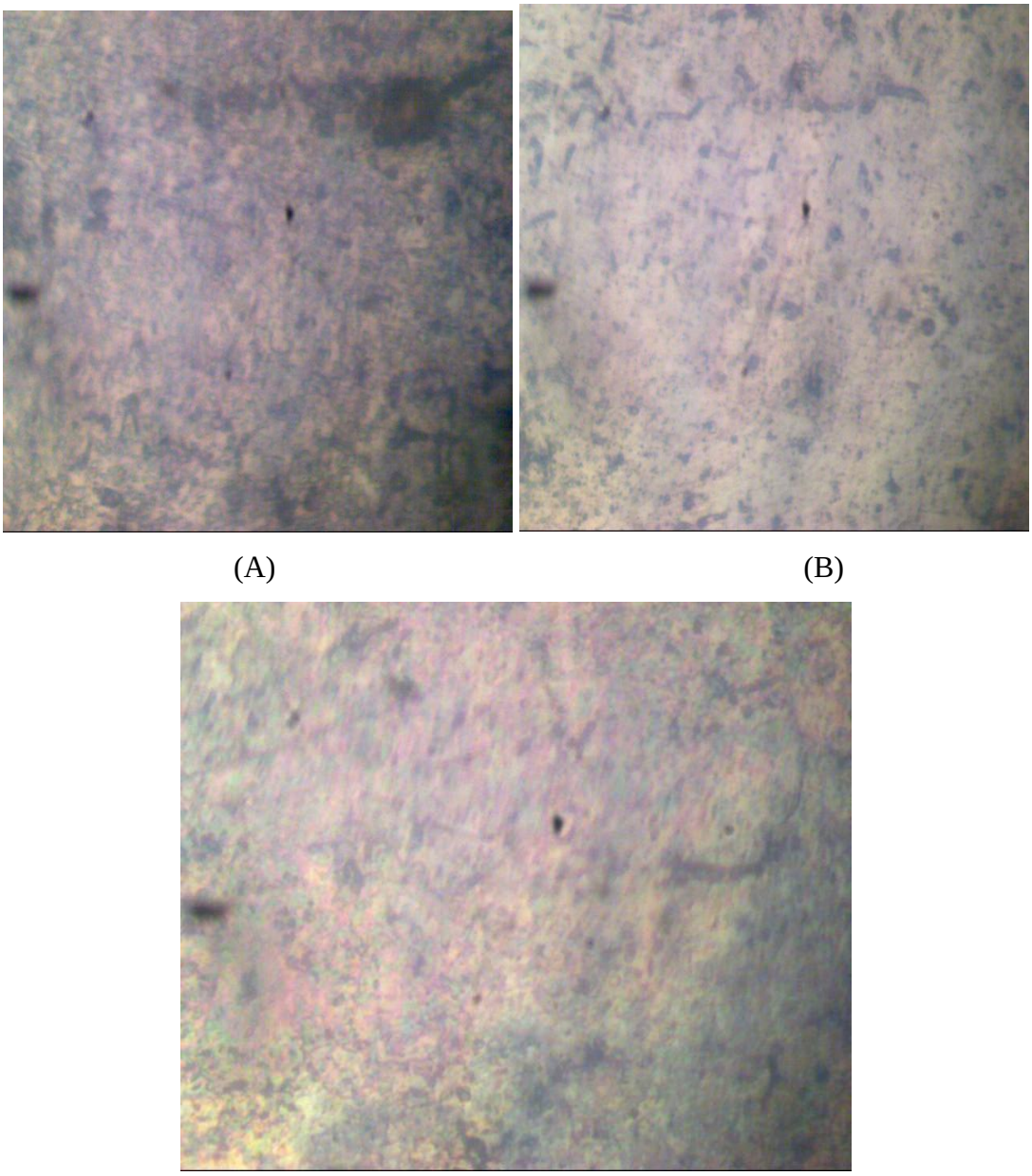
(E)



(F)

Figure 4.7. (A-F) Mechanical properties of normalized specimens heated to 1000^{0}C held for 30 minutes, 60 minutes and 120 minutes.

Fig. 4.8 shows the optical microstructures of specimens heat-treated at 1000^0C. Carbide precipitates could be seen here but negligible in sample soaked for 30 minutes and minimum in sample soaked for 120 minutes, with increasing temperature and exposer time Carbide precipitates are negligible that are due to desensitization which is clearly visible in fig. 4.8 (C).

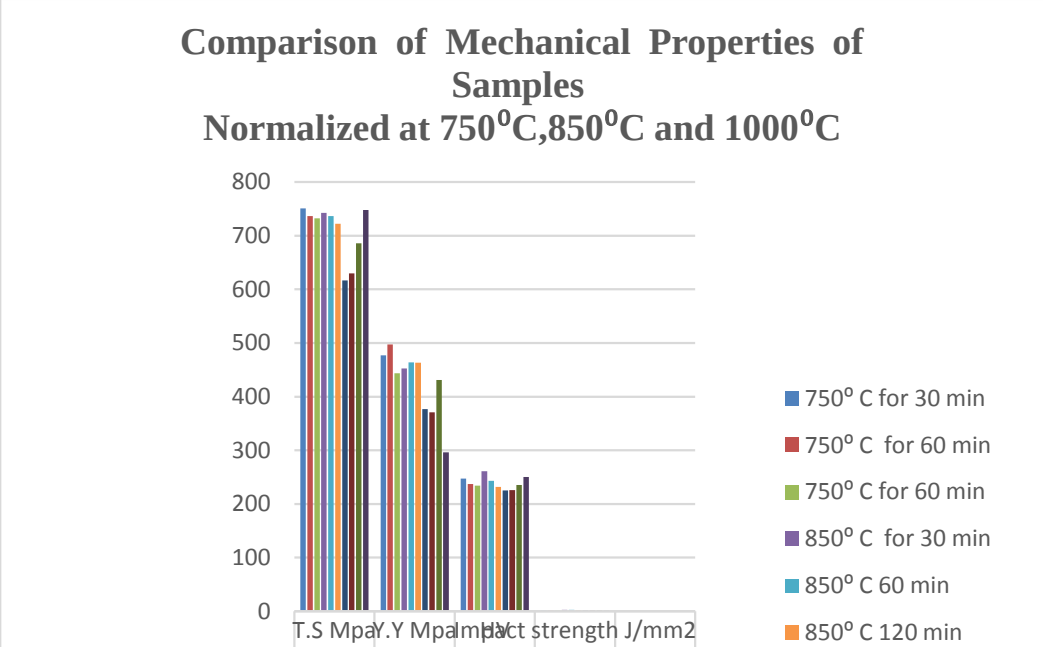


(A) (B)

(C)

Figure 4.8. The optical microstructures of the specimens heat-treated at 1000^0C for (A) 30 minutes, (B) 60 minutes and (C) 120 minutes.

4.5 Comparison of Mechanical Properties of Samples Normalized at 750°C, 850°C and 1000°C



	T.S Mpa	Y.Y Mpa	HV	Impact strength J/mm2
750° C for 30 min	750.78	477.023	247	1.4
750° C for 60 min	736.76	497.196	237	1.28
750° C for 60 min	732.13	443.48	234	1.2
850° C for 30 min	742.63	452.63	261	2.6
850° C 60 min	736.711	463.56	243	2.5
850° C 120 min	722.04	463.15	232	1.9
1000° C for 30 min	616.88	376.52	225	1.84
1000° C for 60 min	629.61	371.03	226	2
1000° C for 120 min	685.93	431.25	235	2.2
welded at 210 A	747.7	296.4	250	1.56

Figure 4.9. Mechanical properties of normalized samples at temperature and as welded sample welded at 210 A.

Chapter 5
Conclusions and Future Scope

5.1 Conclusions

The following conclusions are drawn from this work:

1. SS 304 was observed to go into sensitization when heated to 750^0 C and 850^0 C for 30, 60 and 120 minutes.
2. All the three welds showed good joint strength but best results were achieved under condition of lowest heat input **(2.2 kJ/mm)** in terms of tensile strength and micro hardness obtained viz. **747.70 MPa** and **250 HV** respectively as compared to **787.40 MPa** and **253 HV** of the base metal.
3. Tensile strength was found to be decreases with increasing soaking time and normalization temperature.
4. The hardness of normalized 304 stainless steel was also observed to decreases with increasing soaking time and normalization temperature.
5. Impact strength of normalized 304 stainless steel was also observed to decreases with increasing soaking time and normalization temperature.
6. At 1000^0 C, sensitization was observed at 30 minute soaking time and desensitization was observed at 1 and 2 hrs soaking time.

5.2 Future Scope

1. Effect of different sensitization conditions by varying time and temperature can be studied.
2. Corrosion test can be performed to study the effect of sensitization on corrosion resistance.
3. Sensitization modeling can be done.
4. Welding techniques other than GTAW and be used or comparison between the different welding techniques can be made to study performance of weld joint.
5. Low temperature sensitization (LTS) behavior of the material can be investigated.
6. Desensitization studies can also be incorporated.
7. Same study can be conducted on other low carbon grades of 300 series austenitic stainless steels.

References

[1] ASM Speciality Handbook, Stainless Steels, Welding. Materials Park, OH: ASM International; 1994.

[2] Jong-Hyun Baek, Young-Pyo Kim, Woo-Sik Kim, Kho Young-Tai, "Fracture toughness And fatigue crack growth properties of the base metal and weld metal of a type 304 stainless steel pipeline for LNG transmission int J Press Vessel Pip." 2001; 78:351 -7.

[3] Lippold JC, Kotecki DJ. Welding metallurgy and weldability of stainless steels. New Jersey: Wiley Interscience; 2005.

[4] Sindou Kou.2003.Welding Metallurgy. 2nd Ed. A John Wiley and Sons, INC. Publication. New Jersey.

[5] Korinko P.S and Malene S.H. 2001. "Consideration for weldability of type304L and 316L Stainless steel."ASM Int. 4: 61-68.

[6] American Iron and Steel Institute, Washington, U.S.A. Welding of Stainless Steels and other joining methods. A Designers" Handbook Series No. 9

[7] BOC. Stainless Steel, AU : IPRM 2007,Section 8 : Consumables.333

[8] Parmar R.S. 2008. Welding Engineering and Technology. 5th ed. Khanna Publishers.

[9] Khanna O.P. 2009. A Text Book of Welding Technology.

[10] Wasnik D.N, Kain V, Samajdar I, Verlinden B and De P.K. 20 controlling grainboundary energy to make austenitic stainless steel resistance to intergranular stress corrosion cracking. ASM Int. 12: 402- 407.

[11] American welding society, U.S.A. Classification of Stainless Steel. http:// www .aws.org/w/a/wj/1998/11/kotecki

[12] Rahul Unnikrishnan, K.S.N.Satish Idury, T.P. Ismail, Alok Bhadauria, S.K.Shekhawat, Rajesh K. Khatirkar, Sanjay G. support, " Effect of heat input on the microstructure, residual stresses and corrosion resistance of 304L austenitic stainless steel weldments. " (2014)10-23.

[13] EI Gyun Na, "Evaluation of sensitization and corrosive damages of the weldment for 316 stainless steel." (2013)2715- 2719.

[14] Parag M. Ahmedabadi,Vivek anand Kain, Bhupinder Kumar Dangi, I. Samajdar, "Role of grain boundary nature and residual strain in controlling sensitization of type 304 stainless." Corrosion Science 66 (2013)242– 255.

[15] Mohd Warikh Abd Rashid, Miron Gakim, Zulkifli Mohd, Rosli, Mohd Asyadi-Azam,A.kermanpur, M.Shamanian, V.Esfahani-Yeganesh,"Formation of Cr23C6 during the Sensitization of AISI 304 Stainless Steel and its Effect to Pitting Corrosion." (2012) 9465-9477.

[16] Pilar De Tiedra, Óscar Martín, Manuel López, Manuel San-Juan, "Use of EPR test to study the degree of sensitization in resistance spot welding joints of AISI stunts stainless steel Corrosion Science." 53 (2011) 1563–1570.

[17] Subodh Kumar and Shahi A.S. 2011. "Effect of heat input on the microstructure and mechanical properties of gas tungsten arc welded AISI 304 stainless steel joints. Material and Design." 32: 3617 – 3623.

[18] Atanda P, Fatudimu A and Oluwole O. 2010. "Sensitization study of Normalized 316L Stainless Steel."J Minerals and Materials Characterization and Engg. 9 No.1: 13-23.

[19] K.H. Lo, D. Zeng, C.T. Kwok, "Effects of sensitisation-induced martensitic transformation on the tensile behaviour of 304 austenitic stainless steel." Materials Science and Engineering A 528 (2011) 1003–1007.

[20] Maria de jesus,perez erain almanza carlos rodrigo muniz,russell steel, "Analysis of sensitization phenomenon in friction stir welded 304 stainless steel."front.mater. sci. china 2010 4(4):415-419.

[21] Moura,Y.A.Kina,S.S.M.Tavares,M.S.G.de Faria,F.B.Mainier,"Investigation of cracks and sensitization in an AISI 304L stainless steel exposed to 500– 600 LC." Engineering Failure Analysis 16 (2010) 545–551.

[22] Lima A.S,Nascimento A.M,Abreu H.F.G,DeLima-NetoP.2005."Sensitizati- on evaluation of the austenitic stainless steel AISI 304L, 316L, 321 and 347." J Materials Science. 40: 139-144.

[23] Wasnik D.N, Kain V, Samajdar I, Verlinden B and De P.K. 2003. "Controlling grain boundary energy to make austenitic stainless steel's resistance to intergranular stress corrosion cracking." ASM Int. 12: 402- 407.

[24] Martin Matula, Ludmila Hyspecka, Milan Svobada, Vlastimil Vodarek, Cath erine Degbert, Jacques Galland, Zuzana Stonawska and Ludek Tuma. 2001. "Inter granular corrosion of AISI 316L steel." Material Characterization. 46: 203-210.

[25] Kab Soo Lee, Kyehyun Cho, Tae Hoon Lim, Seong-Ahn Hong and Hwayong Kim. 1999. "Corrosion behavior of sensitized AISI-type 316L stainless steel in molten carbonate fuel cell in cathode-gas environment." J Power Sources. 83: 32-40.

[26] Zumelzu E, Supulveda J, Ibarra M.1999. "Influence of microstructure on the mechanical behavior of welded 316L SS joint." J Materials Processing Technology. 94: 36-40.

[27] Tsai N.S and Eagar T.W. 1984. "The size of sensitization zone in 304 stainless steel welds." J. Materials for Energy Systems. 6: 33-37.

[28] Ahmet Durgutlu. 2004. "Experimental investigation of the effect of hydrogen in argon as a shielding gas on TIG welding of austenitic stainless steel." Material and Design. 25: 19-23.

[29] Jeong Sik Choi and Duk Yong Yoon. 2001. "The temperature dependence of abnormal grain growth and grain boundary faceting in 316L stainless steel." ISIJ Int. 41 No.5: 478-483.

[30] Karzov G.P, Timofeev B.T, and Chernaenko T.A. 2006. "Analysis of the events of the failure of pipelines made of austenitic steels in nuclear power generating industry." Strength of Materials. 30. No.4. 359-366.

[31] Kim Y.H, Lee D.J, Byun J.C, Jung K.H, Kim J.I, Lee H.J, Shin Y.T, Kim S.H, Lee H.W. 2011. "The effect of sigma phase formation depending on Cr/Ni equivalent ratio in AISI 316L weldments. Material and Design." 32: 330-336.

[32] Korinko P.S and Malene S.H. 2001. "Consideration for weldability of type 304L and 316L stainless steel." ASM Int. 4: 61-68.

[33] Raghuvir Singh, Gautam Das, Singh P.K, Chattoraj. 2009. "Low temperature sensitization behaviour of base, heat affected zone and weld pool in AISI 304LN." The Minerals and Material Society and ASM Int. 40A: 1219-1234.

[34] Ramazan Yilmaz and Huseyin Uzun. 2002. "Mechanical properties of austenitic stainless steels welded by GMAW and GTAW." J Marmana for pure and applied science. 18: 97-113.

[35] Shankar V,Gill T P S, Mannan S L and Sundaresan S.2003."Solidification cracking in austenitic stainless steel welds."Sadhana.28, Part 3 and 4:359 -382.

[36] C.J.Van Niekerk and M.Du Toit, "Sensitization Behavior of 11-12% Cr AISI 409 Stainless steel during low heat input welding." The Journal of South Aferican institute of Mining and metallurgy, (2011)

[37] A. Yae Kina et al, "Influence of heat treatments on the intergranular corrosion resistance of the AISI 347 cast and weld metal for high temperature service" Journal of Materials Processing Technology, Vol. 199, (2008), pp-391-395.

[38] R.C.D.Sousa, J.C.C.Filho, "Effects of Solution Heat Treatment on grain growth and Degree of Sensitization of AISI321 Stainless Steel" Journal of Material Science, Vol. 41, (2006), pp- 2381-2386

[39] Ravindra V. Taiwade et al, "Effect of welding apsses in Heat Affected Zone and Tensile properties of AISI 304 Stainless steel and Chrome-Manganese Austenitic stainless steel" ISIJ international, Vol. 53, (2013), pp- 102-109.

[40] F.F.Curiel et al, "Effect of magnetic field applied during gas metal arc welding on the resistance to localized corrosion of the heat affected zone in the AISI 304 stainless steel" Corrosion Science, Vol. 53, (2011), pp- 2393-2399.

[41] Shu-Xin Li et al, "Evaluation of the effect of grain size on chromium carbide precipitation and intergranular corrosion of 316L stainless steel" Corrosion Science, Vol. 66, (2013), pp- 211-216.

[42] M.Laleh, Farzad kargar, "Supression of chromium depletion and sensitization in austenitic stainless steel by surface mechanical attrition treatment" Materials letters, Vol. 65, (2011), pp- 1935-1937.

[43] R.I.Hsieh, "The study of minor elements and shielding gas on penetration in TIG welding of type 304 stainless steel" Journal of Materials Engineering and Performance, Vol. 8, (1999), pp- 68-74.

[44] Ahmet Durgutlu, "Experimental investigation of the effect of hydrogen in agon as a shielding gas on TIG welding of austenitic stainless steel" Materials and design 25, 2004, pp- 19-23.