

## **CHAPTER-1**

### **INTRODUCTION**

#### **1.1 OVERVIEW AND MOTIVATION FOR THE RESEARCH WORK**

The high mechanical strength and superior corrosion resistance of duplex grades is a result of the duplex microstructure ferrite / austenite and the alloying with nitrogen [1]. This high strength gives opportunities for reducing both weight and cost as a thinner material can be used. Low nickel content of the duplex grades makes them price stable [2]. By lowering total material weight, we also lower transportation and assembly costs, reducing environmental impacts even further – making duplex stainless steel a genuine material of the future. Duplex stainless steel grades are superior to standard austenitic grade with respect to stress corrosion cracking resistance. Duplex grades are also resistant to a number of acidic and alkaline environments [3-5].

Because of improved strength and corrosion resistance, Duplex Stainless Steels are most widely used in offshore and marine environment. Conventional Austenitic stainless grade materials are now been slowly replaced by DSS / SDSS. Key factor for this improved mechanical and corrosion resistance are proper phase

balance [6-8]. Obtaining balanced microstructure is possible in controlled environment such as steel mill / tube mill etc., but it is very difficult to maintain phase balance in fabrication industries where welding is the major fabrication method. Uncontrolled heating and cooling cycles in welding makes it difficult to maintain austenite / ferrite phase balance and this become challenge for Welding Engineers to ensure proper welding parameters and cooling rate in order to obtain approximately equal phase balance [9-10]. This becomes the key motivation area for my research to establish welding parameters for improved phase balance.

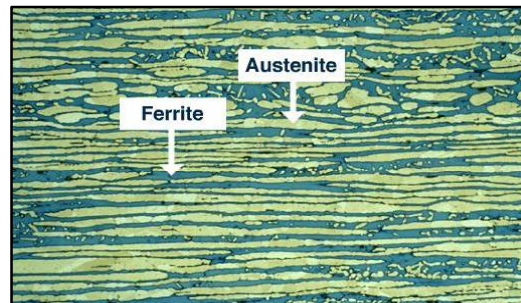
## **1.2 GENERAL**

Stainless steels were first used in early years of twentieth century in Europe. At that time, martensitic and ferritic stainless steels (Fe-Cr) were popular. Later, austenitic stainless steels (Fe-Cr-Ni) were developed which became more popular because of ease in production and fabrication especially in welding applications. In subsequent years, duplex alloys with high Nickel content were developed which accommodated both ferrite and austenite phase in significant amount [11-12, 21]. In 1950s, due to Nickel shortage, scientists were encouraged to develop low-Ni duplex alloys. These new duplex alloys contained balanced ferritic-austenitic microstructure. These steels showed excellent mechanical properties and corrosion resistance than other grades. Since then duplex stainless steels are one of the most popular materials used in various industries and many research studies

[13-18] have been carried out to improve corrosion and mechanical properties of the material.

### 1.3 DUPLEX STAINLESS STEELS (DSS) and SUPER DUPLEX STAINLESS STEEL (SDSS)

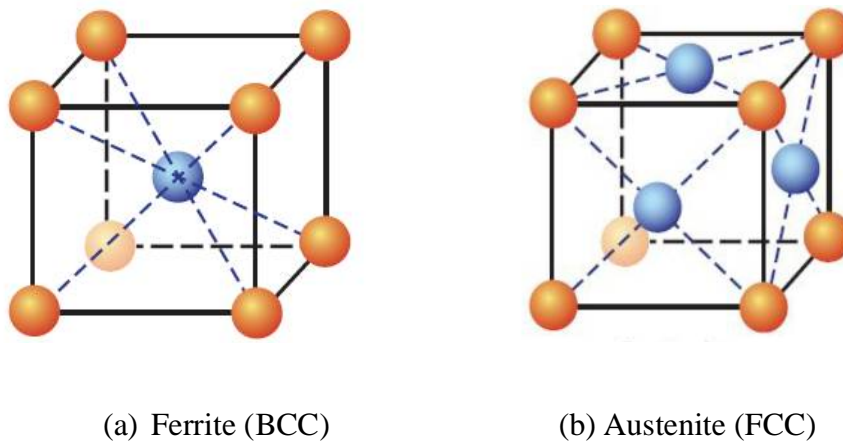
Duplex stainless steels (DSS), 22% Cr, are the family of steels, which combine very good corrosion resistance and mechanical properties. They are characterized by their unique balanced austenitic-ferritic microstructure, which is often called micro-duplex structure [19-20] as shown in Figure 1.1. They exhibit better corrosion resistance than austenitic stainless steels and better toughness and weldability than ferritic stainless steels [20-22].



**Figure 1.1: Microstructure of DSS**

Duplex stainless steels have a dual phase microstructure comprising both austenite and ferrite grains. This microstructure provides an advantageous combination of mechanical properties and corrosion resistance [23]. Ferrite has high strength but poor formability and its high strength is derived from its Body Centered Cubic (BCC) crystalline structure. The BCC structure has no true

close-packed plane; hence, it requires more energy to initiate slip. Austenite has excellent formability, but relatively low strength. Austenite's good formability derives from its Face Centered Cubic (FCC) structure, which has 12 slip systems [24-26]. Thus, the presence of both ferrite and austenite grains serves to increase the overall strength while maintaining sufficient formability for many applications. The duplex structure has formed by adding less nickel than that is necessary for achieving a fully austenitic structure. As the steel solidifies, the BCC ferrite forms first and the FCC austenite forms as the last material solidifies. During subsequent annealing, additional austenite may form by a solid-phase transformation. By volume, a duplex alloy comprises a roughly 50-50 combination of austenite and ferrite grains [27-30]. The crystal structures of ferrite and austenite are shown in Figure 1.2.



**Figure 1.2 – Crystal structure of Ferrite and Austenite**

Super-duplex stainless steel (SDSS) has 25% Cr, 10% Ni and 4% Mo. It is a high-alloy duplex stainless steel with a minimum PRE value of 42 [31]. Very good

chloride corrosion resistance, combined with very high mechanical strength, characterizes the grade. It is particularly suited for use in aggressive environments such as warm chlorinated seawater and chloride containing acidic media [32-35]. The high chromium and molybdenum content of Super Duplex Stainless Steel makes it extremely resistant to uniform corrosion by organic acids like formic and acetic acid. Super Duplex Stainless Steel also has excellent resistance to inorganic acids, especially those containing chlorides [36].

#### **1.4 CHARACTERISTICS OF DUPLEX AND SUPER DUPLEX STAINLESS STEELS**

- High strength
- High general corrosion resistance
- Pitting and crevice corrosion resistance superior to 317L austenitic stainless steel
- Excellent impact toughness
- Good workability and weldability
- High resistance to chloride stress corrosion cracking
- High resistance to corrosion fatigue and erosion
- Good Sulfide stress corrosion resistance

#### **1.5 MECHANICAL AND CORROSION PROPERTIES**

DSS and SDSS have a dual phase structure which results in exceptional mechanical properties. However, these properties depend on orientation i.e. anisotropy. The different orientation is a result of grain elongation and crystallographic texture in rolling operation [37-38].

### **1.5.1 Tensile strength**

Tensile strength of DSS depends on various factors like grain size, ferrite content, solution strengthening of austenite, etc. Between the two phases, for same interstitial content, ferrite is a stronger phase. The solubility of carbon and nitrogen in austenite is much higher than that in ferrite. Therefore, in duplex structure nitrogen is partitioned in a way that austenite can become stronger than ferrite. If nitrogen content in DSS is more than 0.2%, austenite becomes the stronger phase. In super duplex stainless steels, the nitrogen content in austenite may go up to 0.45% and at average content of 0.27 % in alloy [39-40].

In addition, tensile strength is grain-size dependent [41]. If the grain size is smaller / finer, then a duplex alloy achieves higher strength and higher toughness values. The strength of DSS alloy is controlled by stronger ferrite phase, if the effects of partitioning and grain size are compensated.

### **1.5.2 Hardness**

Hardness of DSS depends on grain size, temperature and elemental partitioning. A finer grain size will result in high hardness values. At room temperature, ferrite is a harder phase. However, in hot working temperature region, ferrite becomes

softer phase. The hardness of ferrite may lower down up to one third of the hardness of austenite [42].

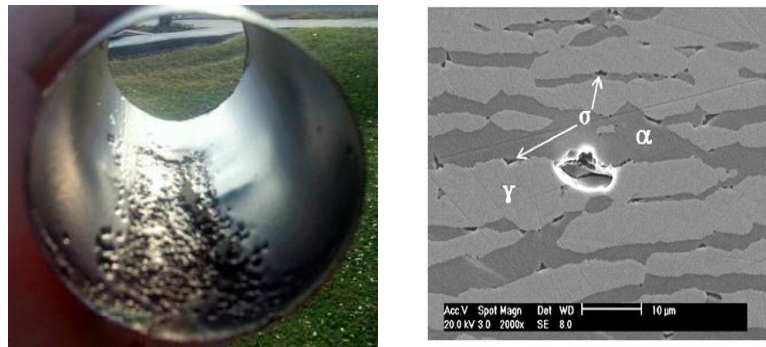
### **1.5.3 Toughness**

DSS achieve higher toughness value than ferritic stainless steels. It is because of FCC structure of austenite phase. Austenite hinders the cleavage fracture of ferrite [43]. However, DSS toughness depends on various parameters such as grain size, austenite content and presence of intermetallic phases. As metallic binding is weak in case of intermetallic phases, it causes bad-deformability of phases, ultimately deteriorating impact toughness of DSS. High alloying contents in super DSS make them susceptible to Sigma ( $\sigma$ ) phase precipitation, which reduces toughness value drastically. In many studies, it has been found that even a small volume fraction of Sigma phase causes drastic reduction in toughness value. Toughness is most sensitive to the precipitation of secondary phases. Intermetallic phases  $\sigma$ ,  $\chi$ , R and  $\pi$  can precipitate when the DSS material reach the temperature range 600-900° C, while at the temperatures below 500° C spinodal decomposition of ferrite takes place which will affect impact toughness. In order to avoid formation of these precipitates, higher cooling rates must be provided [44-47].

### **1.5.4 Pitting Corrosion**

Due to high content of alloying elements such as chromium, molybdenum, nickel and nitrogen, DSS have superior corrosion resistance than austenitic stainless steels [48-49]. In strong oxidizing environments, high Cr content is required while in reducing atmospheres, high Ni content is desired [50].

Pitting is a localized phenomenon, which leads to formation of small pits or holes on metal surface. Pitting is an autocatalytic process [51]. It is initiated at surface defects, which leads to formation of deep cavities in the metal. At the same time, other surface remains defect free. A Pit morphology is shown in Figure 1.3.



**(a) Macroscopic image                      (b) SEM image**

**Figure 1.3 Pit formations in duplex stainless steels**

Pitting behavior of DSS largely depends on chemical composition of material, chloride concentrations, pH value and temperature of the corrosion media [52-54].

Pitting corrosion resistance is measured in terms of Pitting Resistance Equivalent Number (PREN) value, which is given by-

$$PREN_{16} = \% Cr + 3.3 * \% Mo + 16-30 * \% N_2 \text{ [55]} \dots\dots\dots(1.1)$$

$$PREW = \% Cr + 3.3 * [\% Mo + 0.5 * \% W] + 16 * \% N_2 \text{ [56]} \dots\dots\dots(1.2)$$



The  $PREN_{16}$  is used to correlate between pitting resistance and chemical composition. The  $PREN_{20}$  and  $PREN_{30}$  are used to emphasize the importance of Nitrogen in resistance against pitting [56-57]. In a duplex microstructure, Cr and Mo partition to ferrite and  $N_2$  and Ni partition to austenite result in different PREN values for two phases. Hence, the alloying elements should be in appropriate content to get similar PREN values [58-59].

## **1.6 APPLICATIONS OF DSS and SDSS**

Because of attractive mechanical and corrosion properties, DSS find many practical applications. The major applications of DSS include offshore, chemical, food and paper industries where material is subjected to aggressive corrosive environments [60-63]. It is also being used as structural members in nuclear power plants, transportation work. The major applications are:

- Pressure vessels, tanks, piping, and heat exchangers in the chemical processing industry
- Piping, tubing, and heat exchangers for the handling of gas and oil
- Effluent scrubbing systems
- Pulp and paper industry digesters, bleaching equipment, stock-handling systems
- Rotors, fans, shafts, and press rolls requiring combined strength and corrosion resistance
- Cargo tanks for ships and trucks

- Food processing equipment

## **1.7 CLASSIFICATION OF DUPLEX STAINLESS STEELS**

Like austenitic stainless steels, the DSSs are also divided in to three groups based on the chemical composition and mechanical strength. These grades differ in mechanical properties and corrosion performance, which depends on their alloy content. Three modern groups of DSSs have been listed as follows:

### **1.7.1 Lean Duplex Stainless Steel**

Lean Duplex stainless steel has 22% Cr, high Manganese (~5%) content with little Mo (0.3%). It has higher mechanical properties and better SCC than AISI 304 and AISI 316 austenitic stainless steel grades. These grades of duplex stainless steels are widely used in industries as the material cost is lower than normal DSS and improved mechanical and corrosion properties than AISI 304 and AISI 316 materials [64].

### **1.7.2 Standard Duplex Stainless Steel (DSS)**

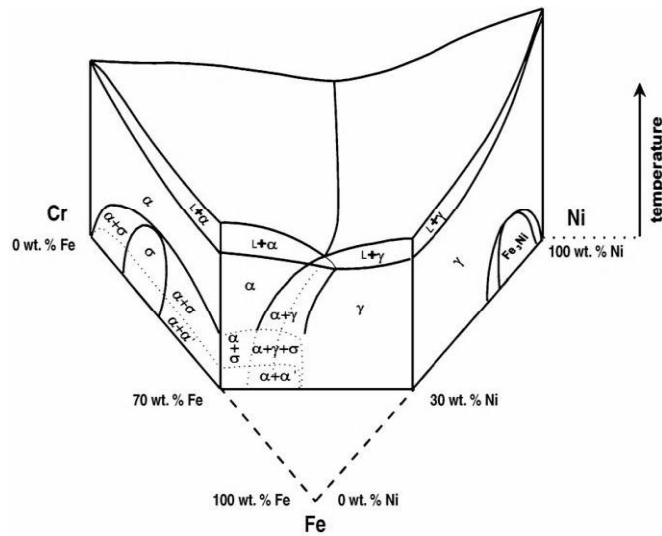
Standard Duplex Stainless steel covers approximately 80% of the duplex usage. The alloying content of DSS materials are 22% Cr, 8% Ni and 3% Mo. These are primarily used because of its improved mechanical and corrosion properties and being cheaper than SDSS materials.

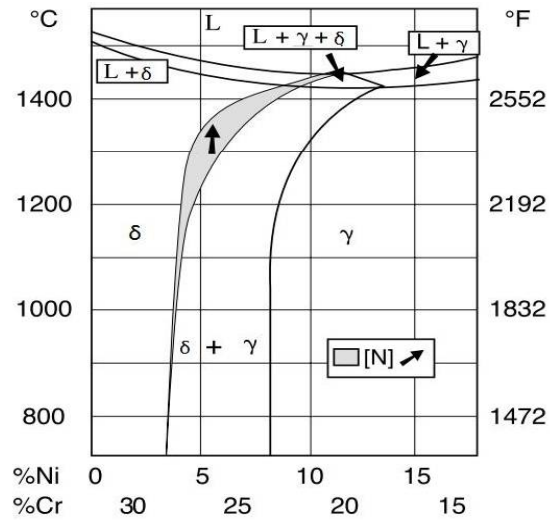
### **1.7.3 Super-Duplex Stainless Steel (SDSS)**

Super Duplex Stainless Steels have high content of alloying elements. They have very high corrosion resistance ( $PREN > 40$ ). These grades are currently available and are widely used in the production of seamless tubes [66]. They pledge cost-effective alternatives to super austenitic steels or nickel-based alloys for heat exchangers cooled by seawater.

## 1.8 PHASE DIAGRAM

The duplex microstructure comprises of 50% ferrite and 50% austenite. The elemental composition is adjusted to obtain this balanced microstructure. The Fe-Cr-Ni system at 70% Fe is shown in Figure 1.4. It shows that DSS alloys solidify into ferrite and later some ferrite is transformed into austenite during cooling [67].





**Figure 1.4- Phase Diagrams of Duplex stainless steels**

However, during cooling from higher temperatures to room temperature, intermetallic phases are precipitated at microstructural level. These can be sigma phase, chromium nitrides, secondary austenite, etc. [68, 69]. The ferrite/austenite phase ratio is controlled by cooling rate as well as by elements, which stabilize these phases. By adjusting thermal cycle and content of Cr, Mo, Ni and N<sub>2</sub>, a desired phase balance can be obtained. It can be seen from phase diagram that how nitrogen affects the austenite formation at high temperatures. As N<sub>2</sub> content is increased, austenite formation takes place at higher temperatures [70].

### 1.9 EFFECT OF ALLOYING ELEMENTS OF DSS

The major alloying elements in duplex stainless steels are Chromium, Molybdenum, Nickel, Nitrogen, Copper, Manganese, Tungsten, etc. [27]. The effect of these alloying elements on properties of DSS is discussed below.

### 1.9.1 Chromium

Chromium acts as a ferrite stabilizer [71.] The major function of Cr is to form a protective oxy-hydroxide film, which improves localized corrosion resistance. However, there is a limit on addition of Cr to steels because higher Cr content facilitates formation of detrimental intermetallic phases in duplex stainless steels [72]. The Cr equivalent in DSS is given as [73]

$$Cr_{eq} = \% Cr + \% Mo + 0.7*\% Nb \dots\dots\dots (1.3)$$

### 1.9.2 Molybdenum

Molybdenum is also a ferrite stabilizer [71]. It protects DSS from pitting and crevice corrosion attack by forming immune oxy-hydroxide layer or molybdate ion. From PREN equations, it is clear that Mo is 3.3 times effective than Cr when pitting is considered [74]. However, higher Mo contents might lead to formation of detrimental chi and sigma phase at higher working temperatures [75].

### 1.9.3 Nickel

Nickel is an austenite stabilizer. The main role of Ni is to control phase balance and element partitioning. In order to maintain balance between ferrite and austenite, the ferrite stabilizers and austenite stabilizers need to be added in appropriate amount. The Ni equivalent is given as [73]

$$Ni_{eq} = \% Ni + 35*\% C + 20*\% N_2 + 0.25*\% Cu \dots\dots\dots(1.4)$$

Nickel reduces current density values and push Electrode potential in noble direction. The high Ni content is desired for corrosion resistance in

reducing atmospheres. The higher Ni content accelerates formation of prime- $\alpha$  phase in ferrite, which leads to embrittlement of the material [72].

#### **1.9.4 Nitrogen**

Nitrogen is also an austenite stabilizer element. It increases pitting resistance, austenite content and strength of an alloy [74]. Nitrogen is found to push electrode potential in noble direction. It has been also found that N increases crevice corrosion resistance [75]. It has favorable effects on DSS as it delays the precipitation of intermetallic phases. However, at the same time, the higher N content causes nitrides precipitation [76].

#### **1.9.5 Manganese**

Addition of Mn to stainless steels increases its wear and abrasion resistance as well as tensile properties without loss of ductility [77]. The higher Mn content increases the temperature range and rate of formation of intermetallic phases. It also forms MnS, which acts as initiation site for formation of pits [78].

#### **1.9.6 Copper**

An addition of copper to stainless steels is known to improve corrosion resistance in non-oxidizing environments like sulphuric acid. It is limited up to 2 % as above that it will reduce hot ductility of steels [79].

### 1.10 OVERVIEW OF VARIOUS INTERMETALLIC PHASES IN DSS and SDSS

Duplex Stainless Steels (DSS) and Super Duplex Stainless Steel (SDSS) have excellent integration of mechanical and corrosion properties. However, the formation of intermetallic phases is a major problem in their usage. The mechanical and corrosion properties are deteriorated due to the presence of intermetallic phases [80-81]. These phases are induced during welding, prolonged exposure to high temperatures, and improper heat treatments. The various intermetallic phases that can occur in DSS and SDSS are tabulated in Table 1.1.

**Table 1.1- Intermetallic phases, Chemical formulae and their temperature range [82]**

<b>Intermetallic Phases</b>	<b>Chemical Formula</b>	<b>Temperature Range (°C)</b>
Sigma	Fe-Cr-Mo	600-1000
Chi	Fe <sub>36</sub> Cr <sub>12</sub> Mo <sub>10</sub>	700-900
Nitrides	CrN <sub>2</sub> /Cr <sub>2</sub> N <sub>2</sub>	700-900
Carbides	M <sub>7</sub> C <sub>3</sub> /M <sub>23</sub> C <sub>6</sub>	550-650
R	Fe-Cr-Mo	550-800
Π	Fe <sub>7</sub> Mo <sub>13</sub> N <sub>4</sub>	550-600

Prime alpha ( $\alpha'$ ) phase	Fe-Cr	475
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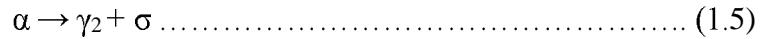
Ferrite to austenite phase balance is desirable In DSS and SDSS. During welding, this balance is disturbed due to ferritization at high temperatures associated with welding process. The high ferrite content is not desirable as it makes the material prone to pitting attack. Hence, filler materials are generally manufactured with higher Ni contents (2-4%) than the base material [83]. Sometimes post weld heat treatments (Solution annealing) are also preferred to retain the phase balance after welding [84]. The heat input and cooling rate in welding are important as they control ferrite to austenite transformation [83, 85]. The high heat input promotes precipitation of sigma phase, nitrides and carbides in heat-affected zones [86]. The welding of thick parts with low heat input is avoided as it may form chromium nitrides [85]. The slow cooling forms more austenite but at the same time, it may cause precipitation of intermetallic phases. Hence, cooling rate is kept low enough to retain phase balance but high enough to avoid intermetallic phase formation [83]. The characteristics of various intermetallic phases are as follows:

### 1.10.1 Sigma phase

Sigma phase is a Cr-Mo rich hard precipitate which occurs at temperatures between 600-1000°C [86-89]. The elements like Cr, Mo, Ni, Si and Mn enhance the formation of Sigma phase. The diffusion of chromium in ferrite is most significant thermodynamic process in the formation of  $\sigma$  phase [91]. Sigma ( $\sigma$ ) is non-magnetic, tetragonal crystalline structure with 30 atoms per cell [92]. This

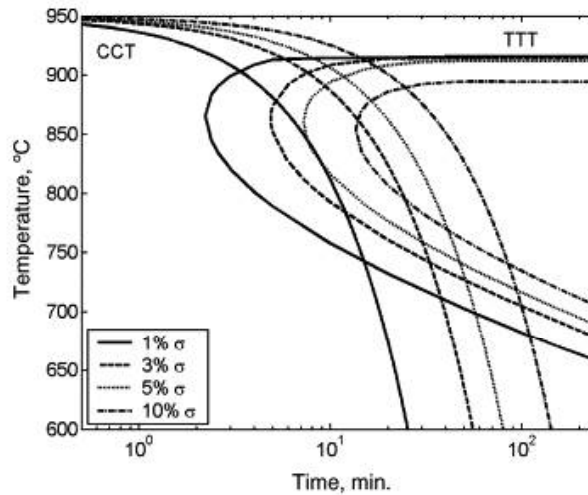


phase occurs due to Eutectoid reaction where ferrite is converted to Sigma ( $\sigma$ ) and secondary austenitic phase ( $\gamma_2$ ) [93].



At temperatures between 850-900 °C, sigma phase has fastest precipitation rate. Sigma phase precipitation starts at  $\alpha/\alpha$  boundaries and  $\alpha/\gamma$  boundaries being to be the high-energy nucleation sites [94]. Later, Sigma phase grows into ferrite phase as the diffusion rate in ferrite phase is 100 times faster than that of austenite, which also makes it a favorable site for precipitation of all intermetallic phases [89].

The precipitation rate of Sigma phase differs with tempering (heating from room temperature) and quenching (cooling from higher temperature) process as shown in Figure 1.5. Few authors concluded that tendency of formation of sigma phase in tempering is very high as compared to quenching process. This can be attributed to the cooling rate required in quenching to form sigma phase is below 1 K/s [95]. The cooling rates in air for fabricated or welded parts of nominal thickness are much higher than 1 K/s. Hence, formation of sigma phase is not promoted.



**Figure 1.5- CCT and TTT curves for sigma phase precipitation [90]**

The precipitation of sigma phase is inevitable in parts with large thickness [96]. The volume content of sigma phase can be minimized by increasing the cooling rate or by adjusting the chemical composition. High cooling rate minimizes the chances of sigma phase formation [95].

### 1.10.2 Chi phase ( $\chi$ )

Chi phase ( $\chi$ ) formation takes place prior to sigma phase formation between temperatures 750 -850 °C. This phase is thermodynamically unstable. Chi phase forms on the ferrite/ferrite interface and grows into the ferrite [97]. As Chi-phase is richer in Mo than sigma phase and Mo being a heavy element, it is easy to contrast between sigma and chi phase using Back-Scattered Electron Microscope (BSE) [97, 98].

### **1.10.3 Secondary Austenite ( $\gamma_2$ )**

Secondary austenite forms with different mechanisms at different temperatures. Below 650 °C, it shows diffusion-less transformation similar to martensitic formation. Between 650-800 °C, it is in the form of Widmanstätten austenite. Here the secondary austenite  $\gamma_2$  formation follows Kurdjumov-Sachs orientation relationship and it takes place with diffusion phenomenon because of its Ni enrichment as compared to ferrite. This austenite is depleted in Cr and N as compared to primary austenite. In between 800-900 °C, with eutectoid reaction  $\gamma_2$  formation takes place [93]. In this reaction,  $\gamma_2$  absorbs Ni, which is austenite stabilizer and rejects Cr and Mo. This causes formation of Cr, Mo rich precipitates like Sigma phase. As  $\gamma_2$  gets depleted in Cr and Mo, they are the favorable sites for pitting corrosion [99].

### **1.10.4 Chromium nitrides (CrN/Cr<sub>2</sub>N)**

Chromium nitrides precipitation is commonly found between temperatures 700-900 °C, during fast cooling from high annealing temperatures. It is because of saturation of ferrite with nitrogen. At higher temperatures nitrogen partitioning increases in ferrite. However, on cooling, solubility starts decreasing thus making ferrite saturated with nitrogen. This forms Cr<sub>2</sub>N at intra-granular sites [100]. Another nitride, CrN forms during welding operations in the Heat affected zone.

### **1.10.5 R-phase**

R-phase precipitates between temperatures 550-650 °C in an initial stage of aging and later, disappears with aging time by transformation to Sigma phase [101]. They form at intra and inter granular sites. R-phase is Mo rich compound and their stability increases with increase in Mo content [101,102].

#### **1.10.6 $\Pi$ -phase**

$\Pi$ -phase formation takes place after isothermal heat treatment at 600 °C for long aging time. This phase is often confused with Sigma phase, as it is also rich in Cr and Mo [27].

#### **1.10.7 $\tau$ -phase**

$\tau$ -phase is a needle like structure which forms at ferrite/ferrite boundaries after heat treatment between 550-650 °C [103].

#### **1.10.8 Alpha Prime ( $\alpha'$ ) phase**

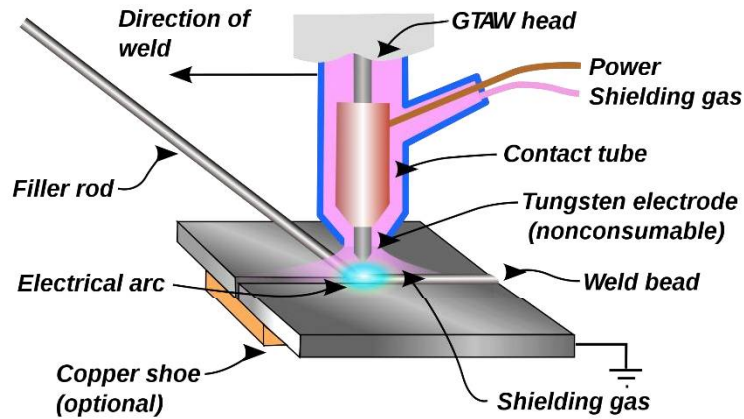
A binary Fe-Cr alloy embrittles in temperature range of 280-500 °C. This embrittlement is caused by decomposition of ferrite phase into  $\alpha$  phase (rich in iron) and  $\alpha'$  phase (rich in chromium). The presence of miscibility gap in Fe-Cr phase diagram causes this embrittlement [104-106]. At 475 °C, the rate of embrittlement is highest, hence this occurrence is known as 475 °C embrittlement.

### **1.11 GAS TUNGSTEN ARC WELDING**

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Fusion welding is a process of creating a permanent joint between metal or non-metal parts by melting of both materials. A permanent bond is created quickly after cooling of molten pool. A filler material is often added while welding of workpieces to create a stronger joint. This is contrary to processes like brazing and soldering, which allow melting of a material with low melting point between the specimens to form a permanent joint. These processes do not involve melting of workpieces. In arc welding technique, an electric arc is maintained between the workpieces and an electrode to melt the specimens by utilizing a power supply. This technique is very popular due to ease in fabrication and low cost. The electric arc is maintained by either using alternating current (AC) or direct current (DC). The electrodes may be consumable or non-consumable. The weld pool is protected from atmospheric contamination by using inert or semi-inert shielding gas [107-110].

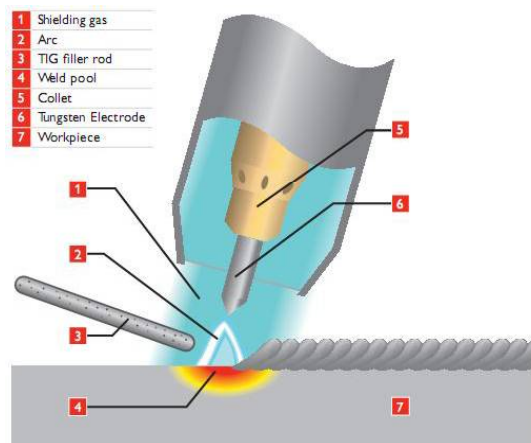
Gas–tungsten arc welding (GTAW) or Tungsten Inert Gas welding (TIG welding) is a fusion welding process that melts and joins metals by heating them with an arc established between a non-consumable tungsten electrode and the metals. The weld area is protected from atmospheric contamination by an inert shielding gas (argon or helium), and a filler metal is normally used. However, some welds do not use filler metals. They are known as autogenous welds [111]. The schematic of GTAW is shown in Figure 1.6.



**Figure 1.6- Schematic representation of GTAW process**

The tungsten electrode is usually in contact with a water-cooled copper tube, called the contact tube, which is connected to the welding cable 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 [112]. The workpiece is connected to the other terminal of the power source through a different cable. The shielding gas goes through the torch body and is directed by a nozzle toward the weld pool to protect it from the air. The torch used in GTAW process is shown in Figure 1.7. Direct current is normally used with electrode negative polarity for welding most metals except aluminium, magnesium and their alloys, because of the refractory oxide film on the surface which persists even when the metal beneath melts. GTAW welding torches are designed for either automatic or manual operation and are equipped with cooling systems using air or water. The automatic and manual torches are similar in construction, but the manual torch has a handle while the automatic torch normally comes with a mounting rack. The angle between the centerline of the handle and the centerline of the tungsten

electrode, known as the head angle, can be varied on some manual torches according to the preference of the operator. Air cooling systems are most often used for low-current operations (up to about 200 A), while water-cooling is required for high-current welding (up to about 600A).



**Figure 1.7- Schematic illustration of the GTAW torch**

Gas tungsten arc welding uses a constant current power source, meaning that the current (and thus the heat) remains relatively constant, even if the arc distance and voltage change. This is important because most applications of GTAW are manual or semiautomatic, requiring that an operator hold the torch. Maintaining a suitably steady arc distance is difficult with a constant voltage power source since it can cause dramatic heat variations and make welding more difficult [112-115].

## **1.12 POLARITY**

There are three types of polarities are used in arc welding namely- a) Direct Current Electrode Negative (DCEN) b) Direct Current Electrode Positive (DCEP)

c) Alternating Current (AC), which are described next [116]. Figure 1.8 shows effect of different polarities on weldments.

**A. *Direct-Current Electrode Negative (DCEN)-***

This is also known as *straight polarity*, which is most commonly used polarity in GTAW process. Here the electrode is connected to negative terminal and workpiece is connected to positive terminal of the welding power supply. Here high velocity electrons are emitted from the negatively charged tungsten electrode and impinged on the workpiece. A high amount of energy is released at workpiece (about two-thirds of total power supplied). The remaining power is located at electrode end. This results in deep and narrow weldments.

**B. *Direct-Current Electrode Positive (DCEP)***

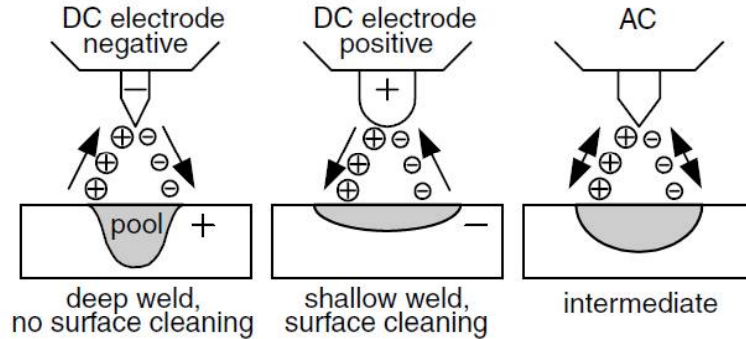
DCEP is also called as the *reverse polarity*. Here the electrode is connected to positive terminal and workpiece is connected to negative terminal of welding power supply. This causes more impingement of electrons at electrode rather than the negatively charged workpiece. Hence, shallow welds are produced in DCEP technique. Generally, water-cooled electrodes are employed to prevent overheating and melting of electrode tip. The positive ions of the shielding gas bombard the workpiece, remove the oxide films, and produce a clean weld surface.



Hence, DCEP can be used for welding of aluminium and magnesium, which are highly oxidizing materials.

### C. *Alternating Current (AC)*

The Alternating Current polarity provides very good penetration and oxide cleaning. This is often used for welding aluminium alloys. The weld defect called arc blow is eliminated in AC polarity because of continuous alternation of polarity.



**Figure 1.8- Different polarities and resulting weld bead shape [116]**

The choice of polarity in GTAW process is based on type of material to be joined. Generally, Direct current negative Electrode (DCEN) is preferred for joining of metal such as ferrous alloys (carbon steels, stainless steels), nickel and titanium alloys, etc. DCEP is seldom used because of low heat input at workpieces and shallow weldments. AC polarity is used for joining of highly reactive materials like aluminium and magnesium. In AC polarity, direction of electron flow changes

continuously. This avoids the overheating of tungsten electrode and results in sufficient heating of the workpieces.

### **1.12 ELECTRODES**

The electrodes used in GTAW process are tungsten electrodes alloyed with 2% thorium or cerium. As compared to pure tungsten electrodes, they offer better electrical conductivity, electron emissivity and contamination resistance. This result in more stable arc and arc initiation takes place at ease. The ability of electrode to emit electrons is known as electron emissivity. Lower electron emissivity produces higher temperature at the electrode tip, which will melt the electrode tip [116-117] reducing electrode life. Thus, it is always better to use alloyed tungsten electrodes for higher electron emission and increased electrode life.

### **1.13 SHIELDING GASES**

In GTAW, inert or semi-inert gases are used to protect weld pool from atmospheric contamination. In general, argon or helium is used. The ionization potential of argon is 15.7eV and for helium, it is 24.5 eV. Hence, argon gas is easier to ionize than helium gas. This makes initiation of arc simpler. In addition, argon gas results in lower potential drop across the arc. One more advantage of argon is that it is heavier than helium. Hence, it makes shielding more effective. Argon also provides better cleaning of oxide films than helium gas. On the other hand, with helium shielding high heat inputs and better sensitivity to arc length

variations can be possible. Argon shielding allows welding of thick sections and welding at higher speeds. Helium shielding allows better arc length control. Hence, it can be used in automatic welding operation. With all above advantages and because of lower costs, argon is mostly used as shielding gas in GTAW process [116-120].

#### **1.14 ADVANTAGES AND DISADVANTAGES**

GTAW is suitable for welding of thin sections because of low heat inputs. The welding current and filler wire feed rate are independent, hence it allows the control of fusion of base metal and filler metal and welding heat input. The use of filler metal is optional. The welding is possible without the filler metal (i.e. only by fusion of workpiece). This is known as autogenous GTAW. In addition, GTAW offers clean weldments (i.e. low splatter and no slag). It can be used in welding of highly reactive materials like aluminium, zirconium, magnesium and titanium, etc. [116, 120-122].

On the other hand, rate of deposition is very low in GTAW, although preheated filler wire can be used to improve deposition rate. In addition, there are chances of melting of tungsten electrode tip. Therefore, this may lead to inclusion of brittle particles of tungsten in weld pool. GTAW uses cooling system, inert gas, etc. hence process is more expensive than conventional arc welding process. The maximum thickness of the work piece that can be welded without use of filler material is 5 mm [116, 122].

### **1.15 APPLICATIONS**

The various applications of GTAW process are as given below [123-125].

- Welding of exotic material like Stainless steel, Duplex Stainless Steel, Inconel, Monel, Cu, Ni, Hastalloy and carbon steel etc.
- Welding of motor casing, engine casing and frames of aircrafts
- Welding of pipes in oil and gas, chemical industries
- Welding of parts in nuclear reactors
- Joining of high pressure steam pipes
- Heat exchangers tube to tube sheet welding etc.

### **1.16 OBJECTIVES**

In order to obtain balanced microstructure of DSS and SDSS weldments for improved corrosion and mechanical properties, the main objectives for this research are:

- To optimize the welding process parameters
- To optimize the heating and cooling rates by controlling inter-pass temperature.
- To optimize N<sub>2</sub> % in Argon shielding and back purging gas to compensate N<sub>2</sub> losses during welding.

## 1.17 WORK PLAN

