Chapter 2

Literature Review

In this chapter, various developments in Gas metal arc welding, Metal transfer in welding and Heat affected zone's mechanical behaviour and optimization techniques have been reviewed. Formation of heat affected zone and metallurgical aspects of welding of low carbon steels and Austenitic stainless steel are discussed and classified. The effect of process parameters on joint properties and heat affected zone has been explored.

Chapter concludes with the discussion on conclusions from the literature and objectives of the present investigation.

2.1 Introduction

The present research aims to investigate the effects of Gas Metal Arc Welding (GMAW) and Heat affected Zone (HAZ) on the mechanical properties of A572 gr. 50 and 316L austenitic stainless steel. GMAW is the most common method for joining long and continuous low and high alloy steels in various industrial processes. It replaces the TIG welding by providing equally high-quality long joints with much higher performance in terms of higher penetration while being economical. Quality weld is the bottom line for every industry. Weld defects visible to the naked eye can be easily detected and sometimes rectified, but defects within the surface or discontinuities need to be specially addressed. Defects in HAZ drastically reduce the service life of overall structure. The important factors tied to welding conditions that influence the weld quality can be improved by using automated systems like GMAW. Defects can occur due to (1) Design related abnormalities (like Wrong weld joint type/ Sudden change in cross section), (2) Welding process related defects (like Lack of fusion, Penetration, Porosity, Inclusions etc.) and/or (3) Metallurgical discontinuities like Cracks or uneven structures(hardness) etc. [22].

GMAW process would be used to evaluate the tensile strength, yield strength, and hardness with emphasis on Heat affected Zone of A572 gr. 50 micro-alloyed steel and substantially alloyed 316L austenitic stainless steel under consideration. Low alloys show large microstructural changes after welding. It is necessary to know about the effect of welding parameters on the mechanical properties of weld joints and HAZ. Highly alloyed stainless steels need special attention due to their low thermal conductivity. So a balance is needed to be struck between welding parameters and mechanical properties. Optical and Scanning Electron Microscopy technique will be used to analyze microstructural changes. Heterogeneity developed during weld thermal cycle may contribute to change metallurgical behaviour and increase the size of critical areas in a welded joint. So it becomes necessary to find the optimum welding parameters in a cost-effective way (through DOE) and parameters that largely control defect and heterogeneity across the weld joint.

2.2 Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding also known as Metal Inert Gas (MIG) welding is an arc welding process which produces the coalescence of metals by heating them with an arc between a continuously fed filler metal/ electrode and the work under a protective environment [23]. The localized heating melts the base metal and the electrode, creating a pool of molten metal (called as crater) results in a fusion bond upon cooling and solidification. Externally supplied shielding gas protects the molten weld pool and upon weld pool solidification a metallurgical bond is created. The arc produces a temperature of about 3593ºC at the tip creating HAZ. Since the joining is an intermixture of metals, the final weldment potentially should have the same properties as the base metal of the parts.

2.2.1 GMAW Basic Welding Circuit

The schematic diagram of GMAW circuit and welding torch is shown in Figure 2.1. the basic circuit contains power source, wire feeder, shielding gas supply and welding gun.

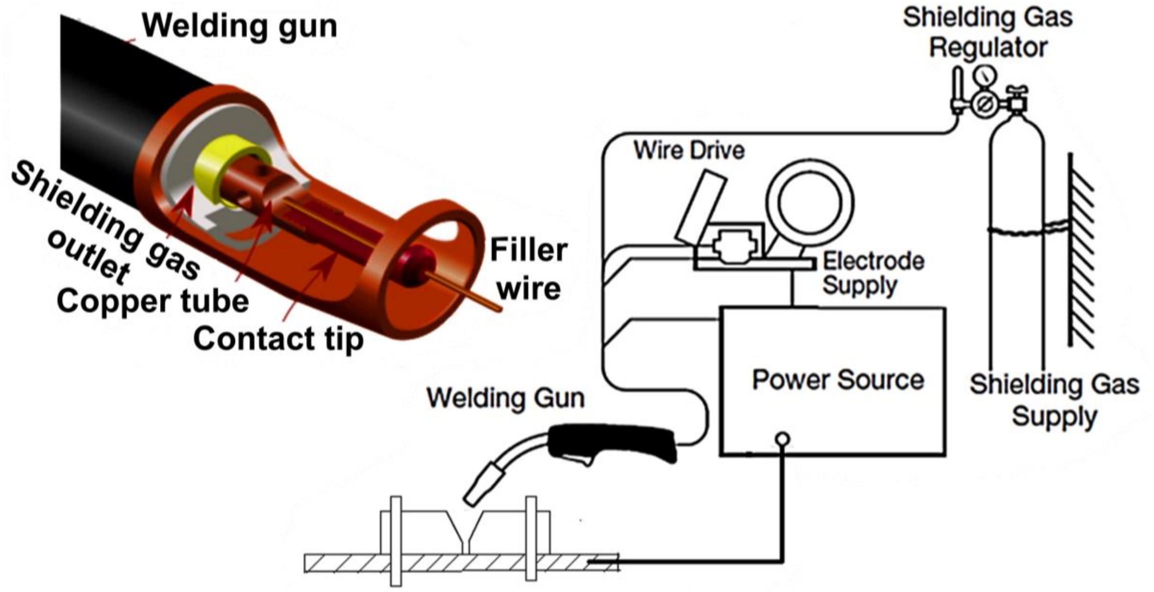

Figure 2.1: Schematic diagram of Gas Metal Arc Welding. Reproduced with permission from Ref. [24] Copyright (2014) Lincoln Global Inc.

DC or AC power source can be used for welding. The electrode, in the form of a roll which is guided through the rollers of the wire driver and through the pipe reaches the welding gun. The electrode is a specially prepared wire that not only conducts the current but melts and supplies filler metal to the joint. Cu coated solid or flux-cored wires are generally used. The intense heat (needed to melt material) produced by the electric arc is manually (by operator) or mechanically (robot/machine) guided along the axis of the joint with proper position and orientation of the torch [24, 25].

Keeping a consistent contact tip-to-work distance (stickout distance) is important because a longer stickout distance can cause the electrode to overheat and will also waste shielding gas. Stickout length varies for different GMAW processes and applications. For short-circuit transfer, the stickout is generally 6.5 mm to 13 mm, while for spray transfer the stickout is generally 12 mm. The orientation of the gun is also important as it dictates the shielding gas flow rate. So it should be held as to bisect the angle between the workpieces that is at 45° for a fillet weld and 7° to 15° from normal for welding a flat surface. The travel angle or lead angle is the angle of the torch with respect to the direction of travel, and it should generally remain approximately vertical or 7-15°. However, the desirable angle changes somewhat depending on the type of shielding gas used. With pure inert gases, the bottom of the torch is out often slightly in front of the upper section, while the opposite is true when the welding atmosphere is carbon dioxide.

2.2.2 GMAW Welding Process parameters

The important parameters that require critical examination for optimization of welding parameters that affect the mechanical and metallurgical characteristics of A572 gr. 50 and 316L SS are Welding current, Arc voltage, Welding Speed/Arc travel speed, Shielding gas and Heat input. The most important parameters whose effect on weld bead (WB) and Heat Affected Zone (HAZ) needs to be thoroughly analyzed are welding current, welding speed, and shielding gas flow rate as they dictate the peak temperature in the weld. Effects of these variables on Gas Metal Arc Welding process and heat affected zone are briefly described below:

a) Welding Current (I)

Heat input and welding current are directly related to each other and on increasing the weld current, heat input increases [26]. It dictates the melting rate of the electrode, the amount of base metal melted, dilution, and the weld bead geometry and heat available for HAZ formation. On increasing the welding current, electrode melting increases along with HI and so is the volume of metal deposited, which ultimately increases the reinforcement and penetration [27]. As current increases, HAZ width may increase with heat input, but if heat input is kept constant, then an increase in current increases the rate of electrode melting, which may not affect the HAZ width much [28]. Wire feed speed is also another parameter that is made in sync with welding current in most of the welding machines and is directly proportional to the welding current. The wire feed speed serves another purpose for regulating the current.

Asibeluo et al. [29] welded A36 carbon steel with SMAW welding process by considering the welding current range from 70-200 A for welding purpose and concluded that on increasing the welding current, there is an increase in HI, which affects the microstructure of the WB and HAZ and impacts the strength and hardness of the welded joint. Rapid cooling promotes smaller grains in HAZ. The increase in welding current and HI, increased cooling time, which facilitated the rapid growth of the grains close to the fusion line and resulted in the degradation of toughness and hardness.

Lim et al. [30] welded 6 mm Rolled SS400 stainless steel with STS304 stainless steel for current values of 100 A and 120 A by both CO_2 welding and MIG welding method. The hardness due to both methods were similar while the tensile and fatigue properties of

MIG welded specimen was superior to CO_2 welded one.

Vasantharaja et al. [31] investigated the residual stresses and distortion on SS 316L using double V and Y grooves at current of 135 A and 285 A. Double V showed minimum distortion and hardness values decreased with an increase of CO_2 in the shielding gas mixtures. A-TIG showed coarser grain size, lower ferrite content and lower residual tensile stresses.

Ajay et al. [32] investigated manual metal arc welding (MMAW) for currents of 150A and 200A and concluded that proper selection of process variables can limit the heat input and control the HAZ width. Heat flow in welding is mainly due to heat input by welding source controlled by weld speed and shielding gases.

Kujanpaa et al. [33] studied the effect of welding parameters on various defects e.g. cracks, centre cavities, cracked centre cavities, ripple cavities, undercut and humps. They concluded that the size and number of defects increase markedly with the welding current. The welding speed affects the character of the defects. Cracks and ripple cavities are formed at low speeds while centre cavities and their cracked versions and undercuts and humps arise due to high speeds.

b) Arc Voltage (V)

An electric arc is the form of electric discharge with the highest current density. The maximum current through an arc is limited only by the external circuit, not by the arc itself [34]. With MMAW and TIG welding, basically set parameter is amperage. Still, it's the arc voltage that fluctuates depending on the length of an arc. The tensile strength and microhardness of weldment increases with arc current, and voltage decreases [35]. Arc voltage affects the weld bead shape and depth of penetration. Bead on plate welds and square edge close butt welds have increased weld bead width and dilution as the arc voltage increases, although depth of penetration is relatively unaffected. A decrease in arc voltage increases the depth of penetration as the narrow arc column is able to reach the bottom of the weld joint [36]. An increase in arc length increases the spatter quantity.

Ragunathan et al. [37] investigated the effect of increasing the welding voltage at constant current and welding speed. Wider, flatter, less penetrated weld beads with reduction in the porosity produced on steel was found. An increase in arc voltage increases the size of droplets and hence decreases the number of droplets. The time of the movement of droplet transfer also increases. Therefore increase in voltage may extinguish the arc and affects the mechanical and metallurgical properties of the joint.

Ogino et al. [38] investigated the Shielding Gas effect on metal transfer phenomena in GMAW for variable current and gas mixture of Ar + CO_2. The results concluded that when the CO_2 content is high in the gas mixture, a high arc current is a must to achieve spray transfer, While when Ar content is high, spray mode of transfer is achieved under high-current values. For pure CO_2 gas, the transfer mode changed to globular transfer at an arc current of 300 A.

Talabi et al. [39] studied the effects of various welding parameters on YS, UTS and toughness of low carbon steel welded joint. It was concluded that an increase in arc voltage and current caused an increase in YS, UTS and toughness.

c) Weld Speed/ Arc Travel Speed(s)

Arc travel speed influences the mechanical properties as well as the microstructure of weldment as it is a function of heat input. The width of weld bead and penetration is controlled by welding speed [40, 41]. On increasing the welding speed, heat input/unit length decreases, as welding speed is inversely proportional to heat input, less filler wire is used/unit length of the weld, resulting in less weld reinforcement. Amount of porosity in a weldment is also influenced by welding speed. **Singh et al.** [42] found slight increase in penetration and the dilution with increase in weld speed (low welding speed) upto optimum weld speed (at constant current) followed by decrease in penetration upon further increase of weld speed. If the welding speed decreases within a certain point, the penetration also decreases, it is only due to the pressure of the large amount of weld pool beneath the electrode, which will reduce the arc penetrating force [43]. Excessive welding speed results in the undercut, arc blow problem, cracking, uneven bead geometry, and also increases the slag inclusion in the weldment.

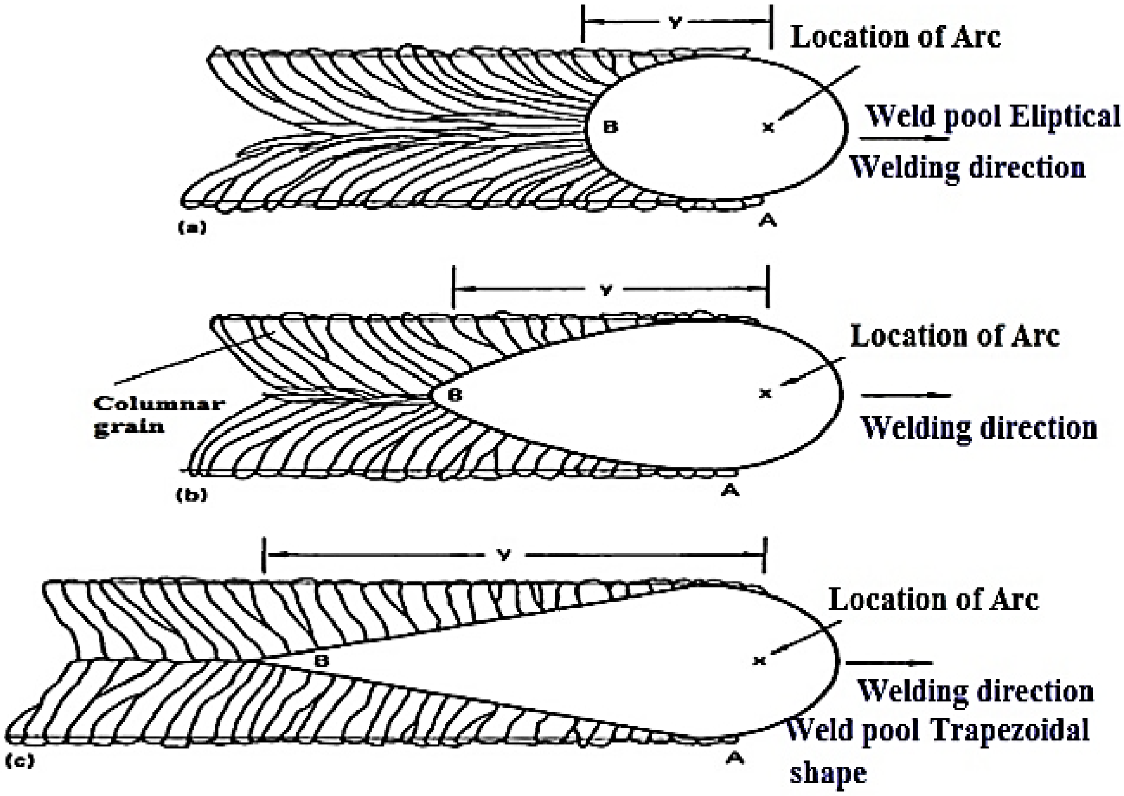

Figure 2.2: Weld pool shapes for travel speed of a) slow, b) intermediate & c) fast. Reproduced with permission from Ref. [41] Copyright (2011) ASM International

Higher welding speed results in fine grain size and narrow HAZ, while a relatively very low welding speed promotes coarse grain in the microstructure. Figure 2.3(a-c) shows weld pool shape change for various travel speeds. **Groong et al.** [40] discussed the effect of bead shape from elliptical to a trapezoidal shape and verified the same.

Weglowski et al. [44] investigated GMAW and effect of current (170-250 A), wire speed (150-240 inch/min) for Weld speed of 1.77-2.55 m/min using tools like F.E.A., Ansys, narrow band filters and high-speed video cameras to investigate HSLA steel. Higher weld speeds showed humping bead (Figure 2.2 b) which were formed at wire feed speeds above 240 inch/min. Results indicated that the wire feed (welding current) has a significant influence on droplet diameter, droplet trajectory and droplet velocity which affects the HAZ and susceptibility to cracking. At lower speeds, the reduction in droplet trajectory and velocity increased the HAZ width and filler droplet diameter reduced from 1.29 mm to 0.15 mm. Similar results were found by **Wang et al.** [45] with large humping beads.

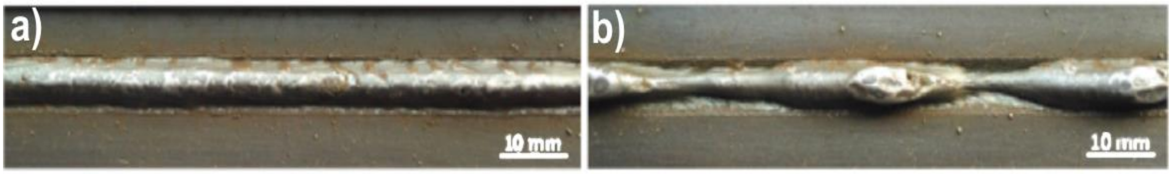

Figure 2.3: Weld back a) Without humping bead at weld speed-1.77 m/min, b) With humping bead at weld speed-2.01 m/min. Reproduced with permission from Ref. [45]. Copyright (2016) Elsevier

Khan et al. [46] MIG welding with root gap of 0 and 2 mm for HSLA was investigated at a variable gas flow rate of 6-20 l/min. Welding speed and shielding gas regulation influence the cooling rate. Higher welding speed may result in underfill or humping beads due to less heat input, considered as a geometrical weld defect, which affects the quality of production.

Srivastava et al. [47] considered welding parameters such as welding speed, wire feed speed, and arc voltage during the welding of IS2062 (MS) steel and they optimized the welding parameters by applying Taguchi's technique. Through ANOVA analysis, they predict the significance of process parameters, wire feed rate followed by arc voltage, and travel speed has been found as the sequence of effective parameter among all uses in this study. The gas flow rate was least effective parameter. Similar results were obtained by **Rizvi et al.** [48] for welding SS 304H using GMAW with 75% Ar and 25% CO_2.

Chuaiphan et al. [49] studied about the effect of welding speed on microstructures, mechanical properties and corrosion behaviour of GTA-welded AISI 201 stainless steel sheets. Welding speeds of 1.5, 2.5 and 3.5 mm/s were used during the TIG welding as shown in Figure 2.4. For the GTAW process, it was found that the joints made using the high welding speed exhibited smaller weld bead size, higher tensile strength and elongation, higher hardness and higher pitting corrosion potentials than those welded with medium and low welding speeds.

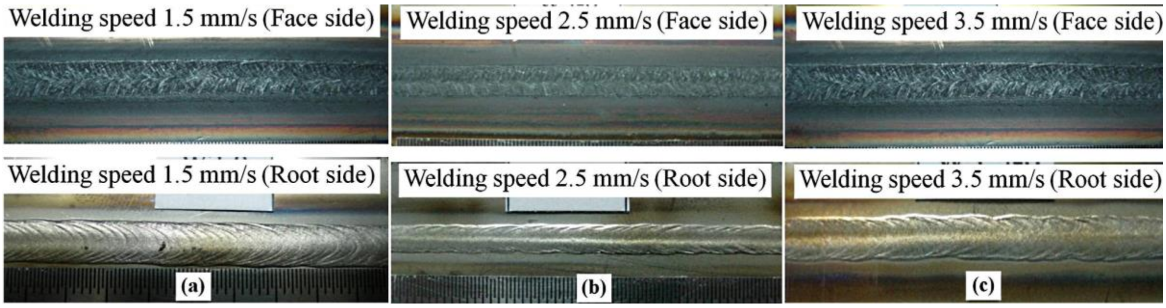

Figure 2.4: Effect of weld speed on 201 stainless steel. Reproduced with permission from Ref. [49] Copyright (2014) Elsevier

Ericsson et al. [50] investigated the effect of welding speed on high-strength steel in TIG and pulse MIG welding. It was found that TIG welds had better fatigue performance at slower welding speeds, but it adversely increased the HI and width of HAZ.

Ojo et al. [51] used a Gleeble Thermo-mechanical simulator for pre-heated samples at 1120°C for 2hr and variable Weld speeds of 76-304 mm/min and investigated hydrogen embrittlement on Ni-based IN 738LC superalloy. Upon cooling, the ductility of the alloy was significantly reduced. HAZ cracking resistance was damaged by liquation reaction involving the precipitate particles.

d) Shielding Gas and its flow rate (f)

During welding, the arc needs to be protected to facilitate quality weld at higher temperatures. While moving an electrode, molten metal can interact chemically with elements in the atmosphere like oxygen and nitrogen, oxides and nitrides degrade the strength and toughness of weld. Therefore, full protection for arc and the molten pool with a protective shield of gas or slag (called as Arc shielding) is a must. Shielding gases in the form of inert gas or a mixture of two or more gases or granular flux, which adds deoxidizers to the weld, are often used in industry. Maximum gas coverage and protection of bead is ensured by sufficient shielding gas and optimum flow rate [52, 53].

Often used shielding gases includes argon, helium, carbon dioxide and di mix or tri-mix of the gases. It affects the finished weld penetration depth and surface profile, porosity, corrosion resistance, strength, hardness and brittleness of the weld material. Effect on bead profile can be seen in Figure 2.5 for mild steel [54]. Mixing of gases provides an advantage in terms of cutting of the overall cost as for welding Stainless steel pure Ar could be costlier with respect to Ar+CO_2/O_2 mixture. CO_2 is widely used as a shielding gas, making it more economical and has boosted its use for welding steels in MIG. In general Ar, He, CO_2, O_2, N_2 and their mixture in various proportions are used for shielding purpose.

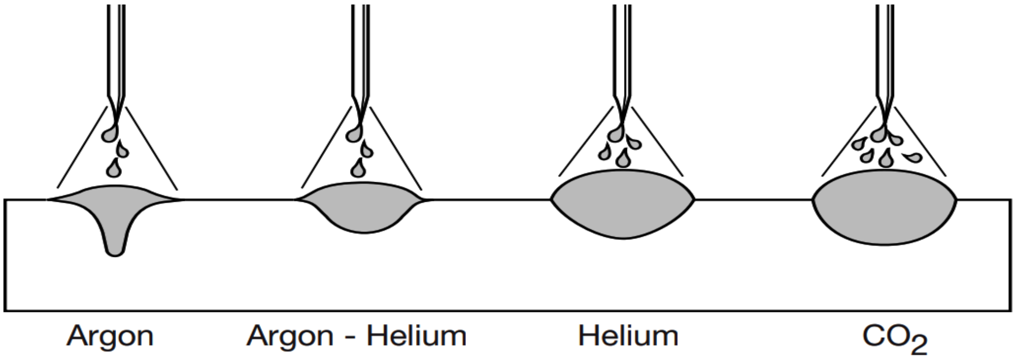

Figure 2.5: Weld bead contour and penetration pattern on Mild Steel. Reproduced with permission from Ref. [54] Copyright (2014) Lincoln Global Inc

Among frequently chosen blends of shielding gases (like Ar+He, Ar+CO_2 , Ar+ CO_2 +He+ O_2 etc.), a blend of CO_2 with Ar being an economical choice (than He) is generally selected, which leads to better arc stability, higher penetration, low spatter and better weld quality [55]. Shielding gas composition and its flow characteristics significantly affect the weld bead surface, heat extraction, and ultimately the mechanical properties. Studies from various reports so far, it can be observed that emphasis has been on the weld metal configuration and properties due to weld cycle. Table 2.1 shows the different shielding gases and their properties for a welded joint [56].

Table 2.1: Shielding gases and their properties for a weld joint

S.No	**CO_2**	**$Ar+CO_2$**	**$Ar+O_2$**	**He**
1	Higher fume levels	Lower fume levels	Lowest fume levels	Lower level of fume
2	Deeper penetration	Shallow penetration	More rounded penetration	Lower penetration than Ar
3	More inconsistent or violent arc transfer	Smoother arc transfer	Smoother arc transfer	Smooth arc transfer
4	Lower cost	Higher cost	Higher cost	Higher cost
5	Higher spatter	Lower spatter	Lowest spatter	Lowest spatter
6	Less radiated heat	More radiated heat	high radiated heat	High radiated heat
7	Less attractive beads	More attractive beads	attractive beads	Highly attractive bead
9	Metal transfer: Spray mode not possible	Spray mode possible	Spray mode possible	Spray mode possible
10	Ferrous alloys	For both ferrous and non-ferrous	Used for stainless steels	Used for non-ferrous materials

linden et al. [56] Investigated Ar & 8/20% CO_2 with different ratios and found that 20% CO_2 Gas mix provided intermediate width and deeper penetration properties due to high current density in weld with CO_2. Also conclude that all shorts of transfer modes can be utilized with CO_2 mixed gas for welding and lack of fusion can be easily controlled.

HAZ in HSLA steels having a soft zone can be deleterious for the welded joint and is of great concern [57]. Shielding gas flow rate too influences the microstructure and the weld bead profile of a weldment. Argon is used in welding of carbon steel, stainless steel, and low thickness plate of aluminum alloys. 5% of H_2 gas is mixed with Ar for frequently joining of Austenitic stainless steels as H_2 increases arc-voltage and consequently heat input, increasing penetration of welded joint and support to improving the weld bead appearance[58]. Different shielding gases and their mixture having different chemical and heat-carrying capacities can significantly dictate the weld quality in terms of defects and heat available for HAZ formation. Different gases behave differently for a specific material.

Ley et al. [59] also considered the effect of shielding gas parameters (composition, supply method and flow rate) on the post-weld thermal properties. A lower shielding gas flow rate exhibited a lower thermal expansion and higher specific heat capacity. lower shielding gas flow rate increase the specific heat capacity and increase the thermal conductivity.

Taban et al. [60] investigated GTAW for welding 304 SS with Pure Ar, and Ar with 5% N_2, 2% H_2 as purging gas. Various purging gases affected corrosion properties as well as the amount of heat that occurred at the roots of the welds only. Mechanical properties were not much affected due to purging gas mixtures.

Moarrefzadeh et al. [61] Studied showed that shielding gas type is the main key of process optimization for GMAW. For low carbon steels, shielding gas mix of CO_2, He, Ar at current of 150 A was investigated. It was deduced that the energy source properties of GMAW strongly depend on the physical property of shielding gas. It was predicted that CO_2 GMA would have excellent energy source properties comparable to that of He, Ar for GMAW for welding ferrous metals.

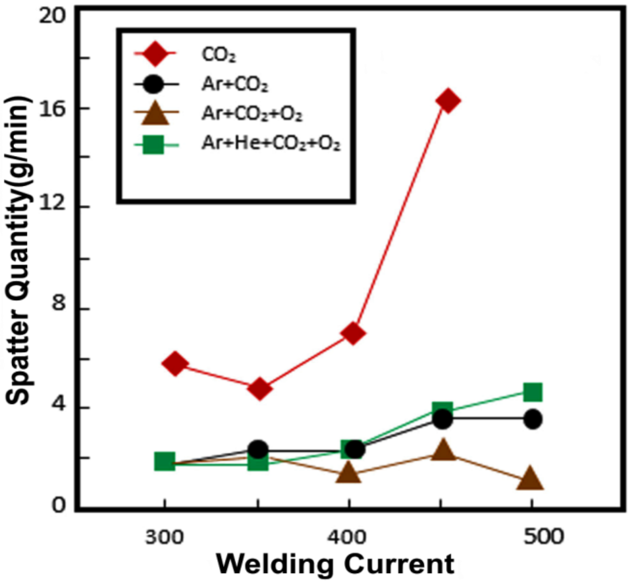

Figure 2.6: Effect of Gas mixture on spatter generation. Reproduced with permission from Ref. [62] Copyright (2016) Springer-Verlag London

Khan et al. [62] investigated the effect of shielding gas on the weldability of high efficient GMAW process on mild steel with a shielding gas mixture of Ar and 5-50% CO_2 with different combinations. Pure CO_2 produced highest (17 g/min) amount of spatter with increasing current upto 500 A. Optimum performance in terms of spatter quantity is achieved with mixtures of inert gases with reducing, oxidizing and reactive gases to increase the melting efficiency of the consumable electrode and the base metal as shown in Figure 2.6.

Gadallah et al. [63] welded Plain Carbon Steel using FCAW for various shielding gas mixtures of Ar & 0, 8, 16, 20% CO_2 at various combinations and investigated mechanical properties. It was found that in the Charpy impact test, the toughness of weld metal decreases with an increase of the CO_2 percentage in the shielding gas composition. Additionally, the hardness of WM decreased with the increase of the CO_2 percentage.

Mukhopadhyay et al. [64] performed welding on HSLA steel using MIG Welding for shielding gas mixture of Ar, CO_2 and O_2. They observed that microstructures of weld bead having constituents such as AF, GF, and Ferrite with Side plate FS are widely influenced by the O_2 and CO_2 content in shielding gas. It was concluded that Yield strength and ultimate tensile strength increased by 4% for a gas mixture of CO_2.

Ebrahimnian et al. [65] studied the influence of shielding gas composition on the weld properties of the ST 37-2 steel. They used two shielding gases i.e. Ar and CO_2 mixture in four proportions and observed that increase in the amount of CO_2 in shielding gas, leads to a reduction of inclusion quantity and porosity on the other hand, volume fraction of acicular ferrite decreased. WB microstructure contained Acicular ferrite(AF), widmanstatten ferrite(WF) and polygonal ferrite(PF) and volume fraction of widmanstatten ferrite increased with increase in the CO_2 amount in shielding gas.

Gulenç et al. [66] investigated the effect of H_2 in Ar as a shielding gas in GMAW of 304 SS and concluded that the increase in hydrogen volume percent in shielding medium the penetration profile, depth, and width of weld bead increased. Figure 2.7(a-c) depicts the lathy to skeletal structure for H_2-Ar shielding at different current ranges.

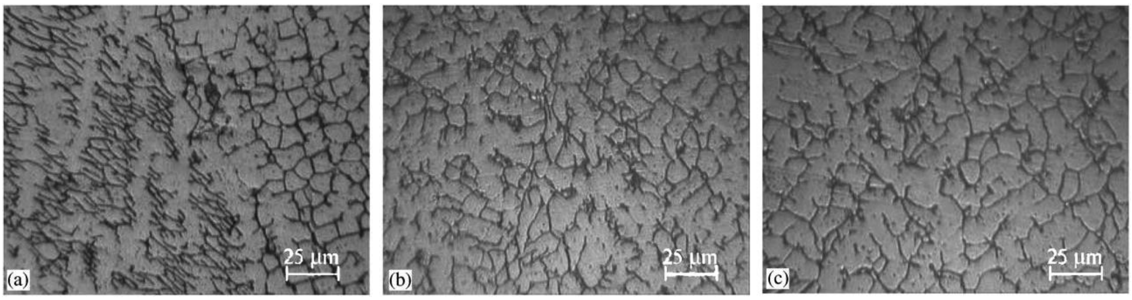

Figure 2.7: Shielding of 1.5% H_2-Ar at current of a) 140A, b) 180A, c) 240A. Reproduced with permission from Ref. [66] Copyright (2018) Elsevier

Katherasan et al. [67] investigated 316LT flux-cored electrode (in GMAW) for various shielding gas mixture of Ar & 05-25% CO_2, Trimix of Ar, 23-25% CO_2+ 2-5% O_2 and 100% CO_2 and found that toughness and ferrite quantity decreased with increasing the percentage of CO_2 in the argon-based shielding gas. The microstructure exhibited a dendrite nature, and the dendrite became coarser as the CO_2 in the shielding gas increased. Inclusion size and volume of inclusions too increased with an increase in CO_2 content in the shielding gas. Hardness values also decreased with an increase of CO_2 in the shielding gas mixtures.

Prabakaran et al. [68] welded 12Cr5Ni2Mo SS using GMAW for Current (160-200 A), Voltage (20-26 V), Shielding gas 100%Ar, 100% CO_2, 80%Ar+20%CO_2. The results showed that micron-sized carbide particles were found dispersed in the matrix of HAZ. 100% CO_2 weld zones have lower δ ferrite content than the 80% Ar+20% CO_2 and 100% Ar. It was due to fast cooling rate that increased austenite stabilizing elements.

Ahmet et al. [69] investigated welding stainless steel 316L SS using TIG with a shielding gas mixture containing Ar and (00-5%)H_2. Mean grain size in the weld metal increased with increasing hydrogen content. Additionally, penetration depth and its width increased with increasing H_2.

e) Heat Input (HI)

Heat input in welding plays an important role in forming different phases/microstructures in WB, FZ and HAZ. A literature review of WB and HAZ cannot be overlooked without a discussion of HI. It is a relative measure of the energy transferred per unit length of a welded joint and HAZ. It is a very important characteristic as it significantly influences the metallurgical structure of WB and HAZ. Heat input has been calculated by the given Equation 2.1 in the material and method section.

Gharibshahiyan et al. [70] MIG welded low carbon steel at variable current (150-350 A), shielding gas flow rate(10-20 l/min) and weld speed and they concluded from their result that at high heat inputs coarse grains appear in the HAZ which lowers the hardness values in CGHAZ zone. High heat input and low cooling rates produced fine austenite grains, resulting in the formation of fine-grained polygonal ferrites at room temperature.

Demarque et al. [71] Investigated Bead on weld for HI range of 0.4 to 2.7 kJ/mm in GMAW with shielding gas mixture of 98% Ar and 2% O_2. Weld speed variation was used to obtain variable HI and evaluate the effect of the thermal cycle on austenitic AISI 316L steels. Results showed a direct relationship between HI, microstructure and ferrite fraction in HAZ. An increase in HI causes an increase in HAZ width. The volume of δ ferrite increased with an increase in HI.

Tabish et al. [72] investigated SS 304 material for their research work and weldment was stronger than base material and strength varied across the welded joint. Low heat input produced fine structured HAZ and from the microstructural study it was revealed that high HI caused grain coarsening with larger dendrites than those produced with medium, and low heat input. Similar results were found by **Muda et al.** [73] on HAZ of ABS grade steel. The microstructure of CGHAZ consisted of grain boundary ferrite, widmanstatten ferrite and pearlite. Grain coarsening at CGHAZ increased significantly along with heat input.

Subodh et al. [74] studied the effect of HI on mechanical properties and microstructure of AISI 304 welded joints by GTA welding and they concluded that joints fabricated at low heat input exhibited higher UTS than those welded with medium and high

HI respectively. It was also concluded that average dendrite length and inter-dendritic spacing in the weld zone increases with increase in the HI, which results in the change of tensile properties of the weld joints.

Juan et al. [75] investigated HQ130 (Super-HSLA) using GMAW under variable conditions of Welding current, weld speed and shielding gas mixture of 80% Ar and 20% CO_2 for generation of defects and cracks for Heat Input of 10-20 kJ/cm. The defects and cracks were found on the surface as well as embedded cracks inside the HAZ. HAZ of was mainly lath martensite, in which there were a lot of dislocations in the sub-structure inside. By controlling weld heat input around 20 kJ/cm, the impact toughness was restored in welded joints suggesting the optimum heat input for good toughness properties.

Sanjeev et al. [76] welded HY 85 (HSLA) steel and simulated the weld joint using Gleeble®3800 Thermo-mechanical Simulator, artificially maintaining Cooling rates of 38°C/s, 25°C/s, and 15°C/s for variable HI from 15 kJ/cm to 50 kJ/cm. Impact tests were also performed at temp 23°C to -196°C. Heat inputs 15 kJ/cm and 22 kJ/cm were found suitable for single-pass welding. A very high amount of coarsening in austenitic grain size is reported in CGHAZ region for HI 50 kJ/cm, while the impact toughness of the CGHAZ for different HIs was decreased with respect to the base metal.

Ekaputra et al. [77] Investigated SS 316L using MIG at variable welding speeds of 175,190 and 205mm/min. The results showed that UTS, YS and Vickers hardness did not change significantly at the welding speed of 175 mm/min due to the occurrence of restoration, while UTS and YS decreased (55%) with an increase in welding speed.

Srinivasan et al. [78] analyzed the effect of heat on fume generation and joint properties of gas metal arc welding on austenitic stainless steel AISI 316. They examined mechanical properties and HAZ microstructure at different HI (0.96, 1.03, 1.15, 1.26 and 1.32 kJ/mm) levels. They concluded that The fume generation rate and fume percentage show a directly proportional relationship with wire feed rate of GMAW process and superior mechanical properties are exhibited for 1.15 kJ/mm HI and welding fume produced are of moderate level.

Ci et al. [79] studied high-strain X80 pipeline steel and found localized brittle zones in the HAZ which were produced because of inhomogeneous hardness and poor toughness. When HI was between 17 kJ/cm and 25 kJ/cm, better impact properties were found in the CGHAZ as the volume fraction of delta ferrite was increased and a slight decrease in hardness as fine M-A constituents size increased.

Pandey [80] used MMAW to weld Double V groove weld for Horton spherical vessel material made of A537 class I steel having a plate thickness of 35 mm which is used for storing LPG gas. The cracks location and their propagation behaviour was studied through SEM examinations ultrasonic technique and found cracks of embedded type, confined in the HAZ. Cracks of 25 to 100 mm in length of embedded type were found 20 mm below the surface. Hydrogen induced during welding developed unfavourable microstructure, high residual stresses and an unsuitable composition of the alloy.

Dean et al. [81] investigated GTAW and studied the effect of multiple passes in butt-welded 9Cr-1Mo steel pipe 21.4 mm for at 300ºC pre-heat by finite element model. It indicated volume change due to austenite to marteniste transformation has a significant influence on welding residual stress. It not only changes the magnitude of the residual stress, but also alters the sign of residual stresses in the weld zone.

Chen et al. [82] investigated SS304 experimentally and by Monte Carlo model which showed that as the inter-pass temperature increased, the width of the fusion zone and the width of grain size in the HAZ increases after the first pass increased.

Toit et al. [83] investigated the susceptibility of 12% Cr type 1.4003 ferritic stainless steel to HAZ sensitization and intergranular stress corrosion cracking. Slow cooling/annealing below 850ºC, austenite decomposes to form desensitized ferrite and carbide precipitates. Upon Examining the influence of multiple pass and rapid cooling of heat-affected zone sensitization on the incidence of intergranular stress corrosion cracking were found.

Zhou et al. [84] Welded A572 gr. 50 steel for L type joint GMAW process for variable current (190-390 A) voltage (20-41 V) and pre-heat temperature of 20°C and 110°C and studied the HI effects for HAZ width. HI of 10 kJ/cm generated narrower HAZ (3mm width) with respect to 40 kJ/cm (9 mm width). The average grain size in CGHAZ at high input was 151 μm, which is two times larger than that at low heat input. The longer cool time would seriously weaken the toughness of HAZ.

Karabulut et al. [85] Investigated Microalloyed Steel joined by SAW for effect of Different Current on Microstructure and Mechanical Properties at current of 350 A, 400 A and 450 A. The results depicted an increase in current or HI; there was increase in hardness and tensile strength due to the formation of widmanstaten ferrite in the transition zone. As HI increases, the HAZ was observed to be much wider at higher welding current (400 A).

Durmusoglu et al. [86] experimented on HY-80 (HSLA) steel using GMAW welding for shielding gas mixture (100% Ar, 80% Ar +20% CO_2 and 100%CO_2) with Pre-heat temp of 55°C along with interpass temperature of 150°C. HAZ hardness values were higher with respect to base material. HAZ creates a transition zone for the material quality and also represents a critical zone at which micro-cracks can occur. Martensite needles and bainite have also been observed in the HAZ.

Silva et al. [87] welded A572 gr. 50 steel using GMAW and FCAW in one and two passes at 195 A under shielding gas of 75% Ar + 25% CO_2. It was concluded that FCAW joints showed superior fatigue life with respect to GMAW in the as-welded condition. The fatigue behaviour was governed by the geometrical aspects of reinforcement which was due to higher wettability in FCAW.

Saadati et al. [88] investigated A572 gr. 50 and gr.80 for mixed shielding gas of 85% Ar and 15% CO_2 using GMAW. It was concluded that Less alloyed material (A572 gr. 50) were less susceptible to hot cracking. Finer grain size of base material and stable nitride and carbonitride precipitates resulted in finer grain size at the HAZ. δ-ferrite at the fusion line, along with a lattice mismatch of less than 15%, facilitated the epitaxial growth.

Winarto et al. [89] investigated SS 316L & SS 304L using TIG welding at variable Current(110-150 A) with an interpass temperature of 150°C and welding speeds of 40,140 and 180 mm/min. The structure and total volume of δ ferrite changed as a result of the welding heat input. The increasing number of weld repairs decreased the percentage of δ ferrite and produces the fine short ferrite precipitates. The HAZ microhardness reduced with increasing weld repair numbers, while the impact strength of both plates was significantly reduced. There was a higher decrease in Impact strength for the 316L plates for repeated weld repairs number, but a few decreased in the 304L plates.

Ma et al. [90] welded 304 stainless steel using a technique of Impacting Trailed Welding (ITW) in which an attempt was made to use MIG welding to reduce the grain size in HAZ. Parameters used MIG tool followed by an impacting tool (spinning hammer at 8 Hz) 30 mm behind the welding gun in the HAZ area. Impact load at temperature in HAZ: 1000°C. With Impact frequency: 25 Hz. The results showed an average grain size reduction by a factor of 2. From first weld pass to second pass, the fibrous structure in HAZ further recrystallized into more refined grains than the normal HAZ.

Yilmaz et al. [91] also studied microhardness welded AISI 316L and AH36 steels using FCAW under shielding gas mixture of Ar with variable CO_2 (0,5 and 10% rest Ar) content. On increase in the amount of CO_2 in shielding gas, impact toughness values of the weld metal decreased. Microhardness values change in weld metal depended on shielding gas composition.

Butola et al. [92] welded SS 304L using MIG process for variable Plate thickness, gas flow rate, welding current and travel speed. It was concluded that micro hardness is greatest in the grain refined region, having the highest Pearlite content whereas the grains are coarser and lowest in hardness in CGHAZ.

Dadfar et al. [93] investigated 316L using TIG welding and performed Heat treatment in Ar environment at 1100°C followed by quenching in water. It was found from electrochemical analysis that Secondary phases in WM caused an increase in corrosion resistance. Also the corrosion rate of a HAZ was more than that of other parts. Solution heat treatment could improve the corrosion behaviour of as-welded 316L SS.

2.2.3 Metal transfer in GMAW

Metal transfer refers to the process of transferring material of the welding wire in the form of liquid droplets to the workpiece. It plays an important role in controlling the process stability and weld quality in WB and HAZ, as the arc dictates the form of filler transfer along with heat input. A negatively charged cathode and a positively charged anode create the intense heat for arc welding. Modes of metal transfer mechanisms that dictate the total heat available for melting and generation of HAZ are as follows [94]:

a) Short-Circuit Metal Transfer

Metal transfer in the form of a single molten droplet of electrode occurs during the shorting phase of the transfer cycle as shown in Figure. 2.8(a). Physical contact of the electrode occurs with the molten weld pool, and the number of short-circuiting events can occur up to 200 times per second. The current delivered by the welding power supply rises, and the rise in current accompanies an increase in the magnetic force applied to the end of the electrode. The electromagnetic field, which surrounds the electrode, provides the force, which squeezes (more commonly known as pinch) the molten droplet from the end of the electrode. Because of the low-heat input associated with short-circuit metal transfer, it is more commonly applied to sheet metal thickness material. However, it has frequently found use for welding the root pass in thicker sections of material in open groove joints.

b) Globular metal transfer

Metal transfer involves a continuously fed solid or metal-cored wire electrode deposited in a combination of short-circuits and gravity-assisted large drops as shown in Figure 2.8(b). During the use of all metal-cored or solid wire electrodes for GMAW, there is a transition where short-circuiting transfer ends and the globular transfer begins. Globular transfer characteristically gives the appearance of large irregularly shaped molten droplets that are larger than the diameter of the electrode. It is a highly stable and efficient process and is widely used in welding thick steel plates and aluminium parts. The irregularly shaped molten droplets do not follow an axial detachment from the electrode. Spatter is severe in this mode of transfer as gravity is instrumental in the transfer of the large molten droplets, with occasional short-circuits. Advantages includes Low cost as its constant voltage equipment and relatively inexpensive CO_2 shielding gas may be used, and higher heat input levels permit the welding of thick sections too. Limitations include excessive spatter, which adds rework (time spent removing spatter), ultimately decreasing the efficiency of the wire supplied (wasted filler metal). It is also limited to the flat and horizontal positions due to large fluid weld puddle.

c) Spray Transfer

Spray metal transfer is the higher energy mode of metal transfer, whereby a continuously fed solid or metal-cored wire electrode is deposited at a higher energy level, resulting in a stream of small molten droplets. The droplets are propelled axially across the arc as shown in Figure 2.8(c). To achieve axial spray transfer, the binary blends containing argon and O_2 (1-5 %) or argon along with CO_2 (up to 18%) are needed. Axial spray transfer may be used with all of the common alloys, including aluminium, magnesium, carbon steel, stainless steel, nickel alloys, and copper alloys. Most of the heat developed by the arc is transferred to the weld pool with consumable electrodes. This mode is used for 6 mm and above thick material, providing higher thermal efficiencies and narrower HAZ zones [54].

d) Pulsed Current transfer

Metal is transferred due to the pulsating current back and forth between globular and spray transfer. Change in current is produced through power source. Principally metal transfer from the electrode is achieved in two ways depending upon the welding current, one at a current below a certain critical current producing a globular mode (less than 10 drops//second) and current producing spray mode (a few 100 drops/second), i.e. around the transition current. Minimum current in globular region is called as background current [94].

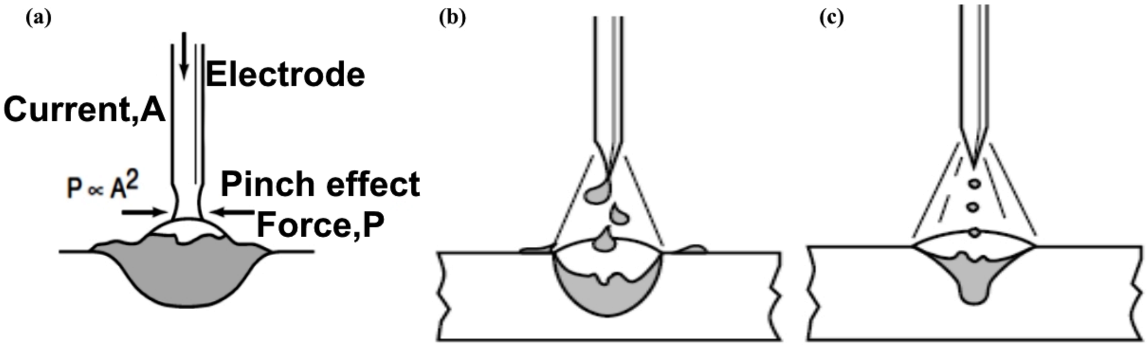

Figure 2.8: a) Short-Circuit Metal Transfer, b) Globular metal transfer, c) Spray Transfer. Reproduced with permission from Ref. [54] Copyright (2014) Lincoln Global Inc

Metal transfer occurs when the peak current is only applied for a few milliseconds, and then the background current takes over. Advantages of pulse welding includes a reduction in spatter, higher deposition rates for out-of-position welding, more resistance to lack of fusion (than short circuit and globular transfer), good on thin materials, reduces fume levels and reduction in overall heat input, which provides the benefit of narrower HAZ. Pulse welding is limited due to higher cost of equipment more expensive than conventional step-down transformer power sources, and the cost of gas blends required. For Stainless steel welding, automated GMAW-P has been recognized as an efficient alternative for minimizing defects [95-97]. For stainless steel welding, the GMAW process needs improvements in order to achieve higher weld quality and higher productivity as its greatly affected by parameters.

2.2.4 Heat Transfer and Metallurgical Changes in GMAW

Heat transfer experiments based on calorimeter reveal that the heat-transfer efficiency for welding thick-section steel is normally 80 to 90%, as indicated in Figure 2.9.

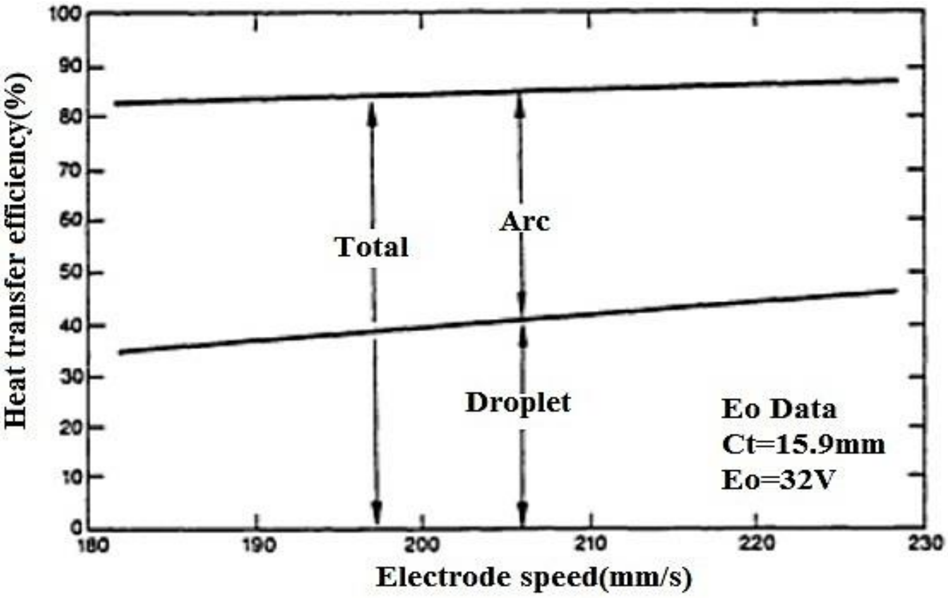

Figure 2.9: Plot of Heat-Transfer Efficiency to Base Metal Vs Electrode-Speed. Reproduced with permission from Ref. [98] Copyright (1993) ASM International

The total heat-transfer efficiency gets altered by changing parameters. It increases slightly as the open-circuit voltage is decreased for a silicon-controlled rectifier regulated power supply. At the same time, it increases slightly with increasing contact tube to work distance [98]. However, 85% is a reasonable estimate for most conditions.

In the GMAW process, the molten droplets of electrode material pass on a significant portion of heat, and it is transferred to the weld pool and HAZ. It can be seen in calorimetry experiments, where the total heat transfer efficiency of the GMAW process is segregated to those portions associated with transfer by the arc and by the molten droplets. At low electrode speeds, about 60% of the total heat transferred is associated with the arc. As electrode speed increases, the fraction of total heat transferred associated with the droplets increases, reaching nominally 50% at current levels in excess of about 220 A for the conditions used.

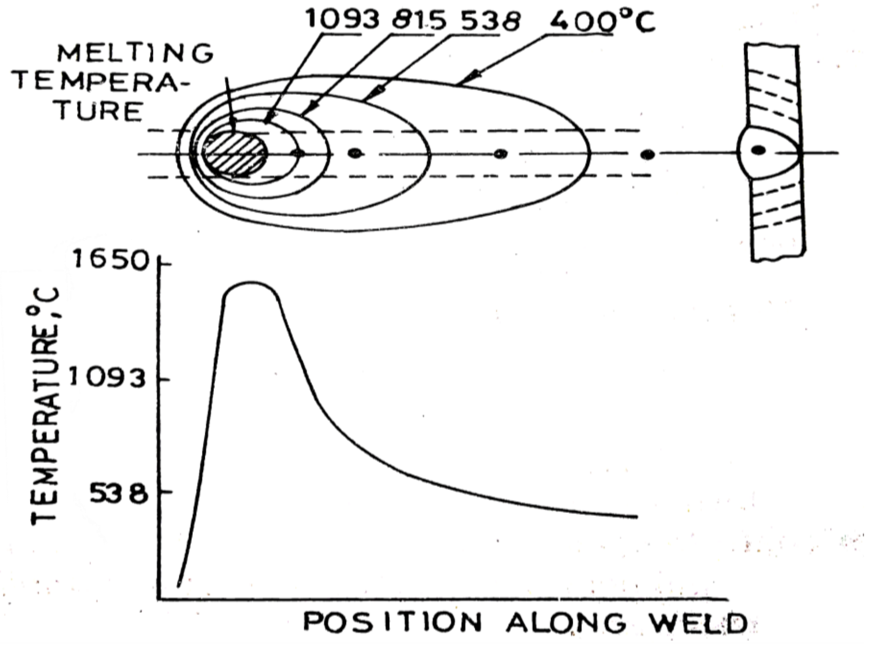

Figure 2.10: Temperature distributions around a metallic arc butt weld. Reproduced with permission from Ref. [99] Copyright (2001) Dhanpat Rai Publications

As the electrode/arc moves from right to left, the leading edge of the temperature pattern is of high density and compressed as shown in Figure 2.10. The arc continually comes in contact with cold metal, and the trailing edge becomes extended because the arc leaves a pre-heated weld portion in its wake. An arc weld made in a high conductivity metal such as Cu or Al does not produce a steep temperature gradient as in a steel weld. In gas welding, base metal is more widely heated but with respect to arc welding the temperature gradient is less severe [94].

GMAW process welded joint metallurgy is considerably affected by re-solidification of the parent metal and molten electrode as an integrated mass under the equivalence of chill casting conditions. It results in the redistribution of micro constituents and the alloying elements in the weld metal zone. Also, the base metal is subjected to complex heat treatment in the form of a temperature gradient followed by a cooling cycle induced by the neighbouring cold metal and atmosphere in HAZ. The temperature and the phase changes in and around the weld introduce volume changes which result in the plastic flow, residual stresses and sometimes cracking too. The area adjacent to a weld pool receives thermal energy in three ways: Conduction through base metal, Radiation from the arc source, and Pre-heat, if employed. The temperature rise stimulates the mode of transformation, which is governed by subsequent cooling rate as the arc moves away and the material continuously loses heat to the surroundings. Therefore, locations near the weld pool experiences rapid heating and cooling cycle together within a short time. The thermal cycle introduced during heating causes the metal to be heated over a range of temperatures (up to fusion) and followed by cooling to ambient temperatures. As the metal away from the weld will be simply warmed out, but as the weld area is approached, progressively higher temperatures are obtained, resulting in a corresponding complex mixture of microstructure, particularly in steel.

Goose et al. [100] examined the effect of varying welding procedures on HAZ toughness of 12% Cr austenitic-ferritic steels. They concluded from their experiment that increasing arc power over the range of 0.5 to 2.0 kJ/mm (13 to 50 kJ/in) caused some increase in ferrite grain size. Reheating promoted further grain growth, but only in the regions close to the solidus temperature. The martensite content in the coarse grain HAZ was determined mainly by the steel composition and the initial high-temperature thermal cycle. They further concluded that HAZ toughness depended mainly on the ferrite grain size produced by welding. Hence, low arc energy is recommended for optimum HAZ toughness.

Gowrishankar et al. [101] investigated the effect of the number of passes on the structure and properties of AISI 316L stainless steel weld prepared by submerged arc welding. They examined welded specimens welded in 5, 9 and 13 passes for mechanical properties and their microstructure. Their results concluded that an increase in the number of passes, increases the minimum delta ferrite content in the root region of the weld. Increasing the number of passes increases the hardness and tensile strength of welds.

In industry, welded structures involve various phases, including the metallurgical analysis for long-term usage in its service life. Regardless of the process employed, the thermal cycle involved during welding results in a heterogeneous mixture of different microstructural phases with different morphology in and around weld. The heating and cooling results in internal stresses and plastic strain in the vicinity of the weld. At higher temperatures, certain chemical changes are liable to take place, which may force physical, chemical and metallurgical properties to change. Figure 2.11 shows the thermal gradient during the welding process [99]. Depending upon the welding process used and the metal being welded, wide variations exist in the maximum liquid temperature and the slope of temperature gradient curve for an unfused metal. The slope of thermal gradient depends upon the way in which heat is being supplied per unit volume of metal, per unit time and the thermal conductivity of base metal parts. The HAZ is wider for gas welding and submerged arc welding than GMAW welding because heat is concentrated for a longer time in these processes. As a rule, the flow of heat in the weld zone is highly directional towards the adjacent cold metal, thereby producing what is called as columnar grains at right angles to the fusion line. The columnar structure is a characteristic of the metal of single-pass welds. Thus the original structure consisting of ferrite and pearlite in steels gets transformed into another microstructure as in A572 alloy. As the liquid of weld pool freezing proceeds, the crystals readjust their composition to that of the initial liquid alloy in order to satisfy the condition of equilibrium. Figure 2.19(a) illustrates the structure of the fusion welding process. The alloying elements like Mn, P, S, Si, Ni, Cu, Cr, Mo, V, Al and Ti improve the microstructure and physical properties across the welded joint by raising and lowering the transition temperature (i.e., the temperature at which material ceases to

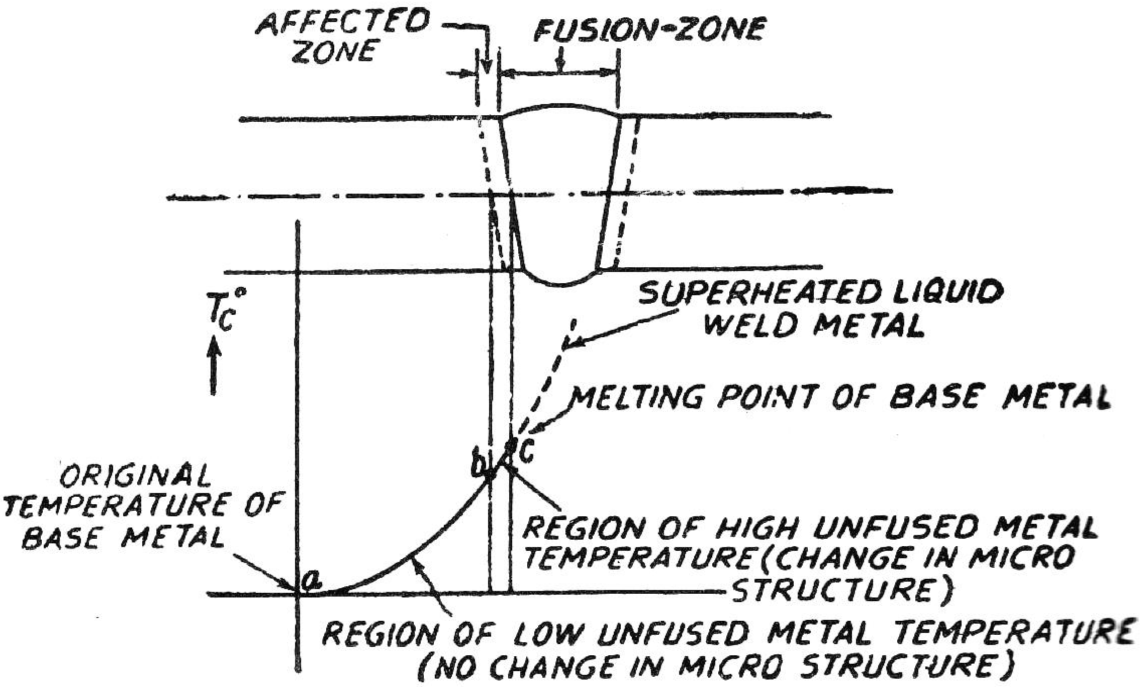

Figure 2.11: Graph showing the change in thermal conditions. Reproduced with permission from Ref. [99] Copyright (2001) Dhanpat Rai Publications

display ductile properties and becomes brittle). The joint's metallurgical properties are also improved by forming intermetallic compounds, carbides or through solid solution strengthening.

2.2.5 Weld Metal and Heat Affected Zone

Weld metal is the portion of the weld joint which is largely affected by defects during the solidification process after welding, while Heat Affected Zone is that portion that features the metallurgical changes due to the heat rejected from the weld metal during and after solidification. The arc heat creates three distinct zones: fusion zone (FZ), Heat Affected Zone (HAZ) and unaffected base metal. Heat for fusion welding produces a very high temperature, and the high cooling rate creates sharply defined isolated zones. Fig. 2.12 (a-b) shows the structure of a weld joint for mild steel. Directional cooling causes columnar (long elongated) crystals to form near fusion faces directed towards the center of weld, and since the inner part of weld cools more uniformly, it results in an enlarged but regular crystal structure. Surface of weld being in contact with air cools very fast and a small and

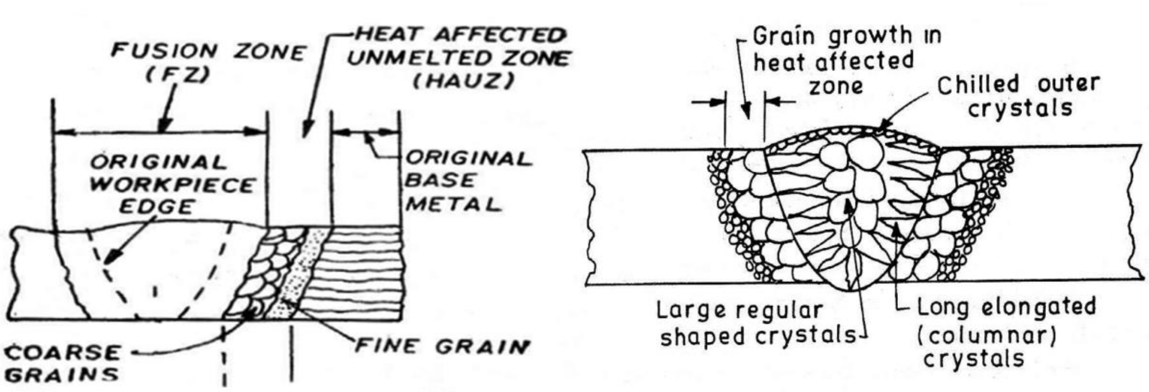

Figure 2.12: Structure of a) Fusion weld joint, b) Structure of Weld metal. Reproduced with permission from Ref. [99] Copyright (2001) Dhanpat Rai Publications

slightly chilled crystal structure can be noted there. The parent metal in heat affected zone experiences grain growth [103].

Hu et al. [104] Investigated structure property relationships in HAZ of GMAW V–N micro-alloyed steel. Different zones of weld joint are as shown in Figure 2.13. The base metal consists of 5-10 µm fine-grained polygonal along with 1-4 µm acicular ferrite plates. Features like acicular ferrite, granular bainite, and a few polygonal ferrites were also found in CGHAZ, while FGHAZ consists of fine-grained polygonal ferrite with grain size around 2-5µm. High fraction of high angle misorientation boundaries in WM, CGHAZ, and FGHAZ and the formation of acicular ferrite in CGHAZ and fine-grained polygonal ferrite in FGHAZ mutually improved hardness and toughness values.

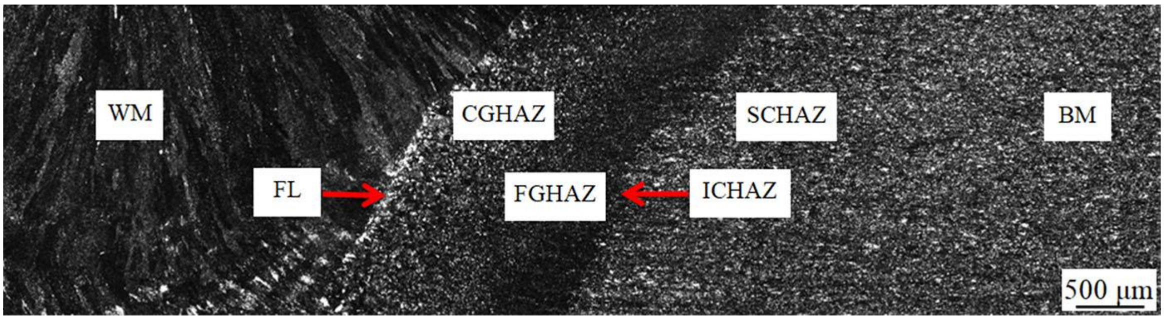

Figure 2.13: Optical micrograph of weld joint. Reproduced with permission from Ref. [104] Copyright (2018) Elsevier

a) Weld Metal (WM)

The weld metal is a fusion zone in which the filler wire melts in the groove and solidifies and bonds with the base plate. The weld metal in the molten state has a good capacity to dissolve gases that come into contact with it, such as oxygen, nitrogen and hydrogen. As the metal starts cooling, the capacity of dissolving gases goes on decreasing, thus causing an additional volume of gases to be evolved. It's the time when the metal becomes mushy and becomes incapable of permitting the gases to escape freely. The entrapment of gases causes gas pockets and porosity in the final weld. A shielding gas or gas mixture is used to avoid any contamination of molten metal pool from the atmosphere. Weld metal or weld zone consists of a columnar solidification microstructure similar to a cast structure [105]. Microstructures of weld metal or weld zone (fusion zone) are greatly controlled by the weld metal composition, and microstructure development in weld zone also depends upon the behaviour of solidification. The basic function of solidification is to control the shape and size of grains, segregation, inclusion quantity and porosity distribution. Solidification also promotes hot cracking in the weld zone [106]. The solidification of metals is usually considered by nucleation and growth process, i.e., a transformation of a liquid phase to a solid normally occurs by process of nucleation growth. Nucleation phenomena is classified as homogeneous or as heterogeneous depending upon the nucleation events that occur without or under the influence of impurities, inoculants or external surfaces. Nucleation involves the creation of critical sized particles (i.e., nuclei) of the new (i.e., solid) phase and considerable super cooling is usually required before the first solid nuclei are formed from which growth may proceed. Growth occurs after nucleation or in the presence of a pre-existing solid/liquid interface by the addition of atoms to the solid [107].

For welded stainless steel joints, the differences between the parent material and filler metal compositions, along with the effect of dilution and composition of weld metal after welding, can be understood by Schaeffler diagram. As the weld pool combines, the base and filler material can create an entirely different structure depending upon the mode of solidification. Schaeffler diagram is a powerful tool to predict the Cr-Ni austenite, austenite-ferrite or austenite-martensite weld having 0.12% carbon. Depending on the alloying elements it contains, the Schaeffler diagram provides information on the various phases (structures) present [108]. In Schaeffler diagram, the austenite or ferrite, the stabilizing effect of each alloying element relative to Cr/Ni respectively, is calculated by their efficiency coefficient in the Cr or Ni equivalent formula and elements are used in weight percentage. For example, 1.8%Mo means 1.8% molybdenum by weight. The original Ni_{eq} and Cr_{eq} formula used by Schaeffler is given below:

$$Ni_{eq} = \%\,Ni + 30\%\,C + 0.5\%\,Mn \qquad \text{… Equation 2.2}$$

$$Cr_{eq} = \%Cr + 1.8\%Mo + 2.5\%Si + 2\%\,Nb \qquad \text{… Equation 2.3}$$

b) Heat Affected Zone (HAZ)

The portion of the base metal that was not melted during welding, brazing or cutting but whose microstructure and mechanical properties were altered by the heat is called as Heat Affected Zone. The un-melted parent metal that gets heated to high temperature for sufficient time is compelled to change its mechanical properties and microstructure. HAZ consists series of graded structures and contains a variety of microstructures. In plane carbon steels, these structures may range from hard martensite to coarse pearlite. This causes HAZ to be the weakest area in the weldment. Most of the weld failures occur in this region.

Depending upon the peak temperature reached, the HAZ can be sub-divided into Coarse Grain HAZ (CGHAZ), fine-grained HAZ (FGHAZ), Intercritical HAZ (ICHAZ) and subcritical HAZ (SCHAZ) zone. Various zones for low carbon steel have been schematically shown in Figure 2.14 [109]. Starting from the weld metal side just after weld bead there exhist a solid-liquid transition zone and extends up to the fusion boundary zone. (1) Grain Growth Zone (CGHAZ) is heated beyond 1150°C to peritectic temperature. (2)

In Grain Refined Zone (FGHAZ) heated from 950°C to 1150°C, i.e., beyond AC_3 up to grain refined temperature range. (3)Partially Transformed Zone (ICHAZ) heated in 750°C to 950°C, i.e. between AC_1 and AC_3 temperature. (4) Over Tempered Zone /Zone of Spherodized Carbides heated from 550 to 750°C below AC_1. The remaining part is the base material with an unchanged structure [110].

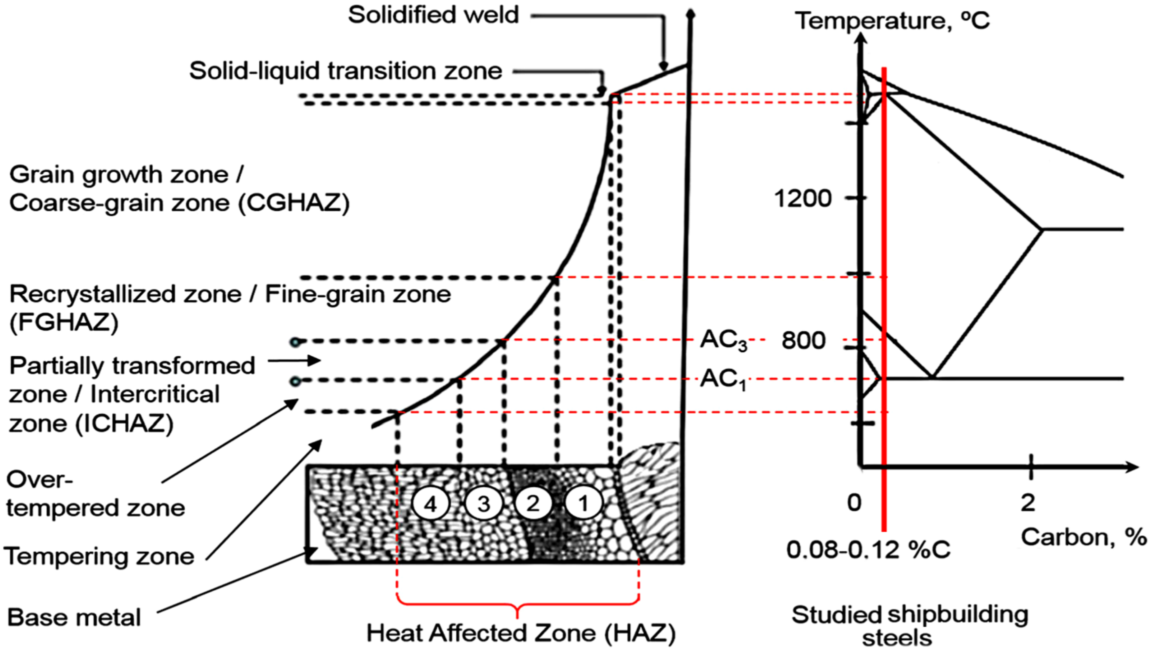

Figure 2.14: Sub-divisions of HAZ for low carbon steel welds and temperature ranges on Fe-C equilibrium diagram. Reproduced from Ref. [109] Copyright (2018) Pavel Layus

Among these, CGHAZ is the most affected region during welding operation due to swift cooling which causes hardening, which in turn can be the most important factor of cleavage cracking. Figure 2.15 shows the formation of coarse grain heat affected zone. Although it is often said that the HAZ is heat-treated part of weld, but there is a considerable difference between welding and heat-treating of steels and its structure. Near the fusion boundary of a weld, where difficulties such as grain coarsening and under-bead cracking often arise, the peak temperature can reach up to 1400°C or even higher, while for heat treatment of steels is around 950-1050°C [104-107]. The high heating rate, together with the short high temperature retention time (except for ESW, SAW) can invariably result in the formation of non-homogeneous austenite during welding. Such non-homogeneous austenite, upon subsequent rapid cooling, can cause the formation of localized high carbon martensite colonies [111]. Consequently, the micro-hardness of the HAZ tends to scatter over a wide range and usually depends upon heat input, composition, peak temperature, heating and cooling rate, and electrode angle. The microstructure in welded joints is too much influenced by the various factors such as base metal composition, filler wire used, shielding gas used, and actual cooling rate experienced by the weldment during the transformation of austenite to ferrite. The phase transformation that occurs during the welding process is of major importance in determining the metallurgical and mechanical properties of both the weld metal and the HAZ in a welded joint. The transformation in the weld metals is governed by cooling cycle as well as subsequent thermal history of succeeding passes. However, the HAZ experiences a cooling rate faster than that the critical rate from a temperature above AC_1 will result in the formation of hard, brittle martensite, which is accompanied by generation of stress. The stresses can be further accumulated by delayed (γ-α) changes in a closely adjacent zone (The γ-α changes in volume in expansion of lattice) as a result of temperature gradient. Also lower the transformation temperature, the greater is the effect of volume change on the more rigid lattice structure during the changes. So

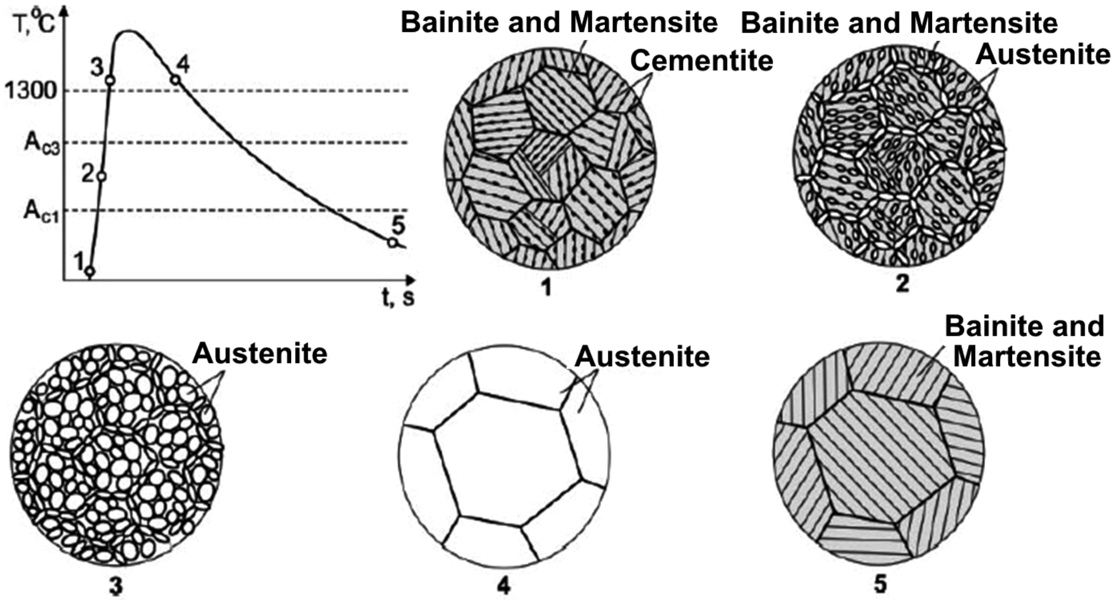

Figure 2.15: Schematic of CGHAZ formations. Reproduced with permission from Ref. [111] Copyright (2013) LUT, Finland

greater is the tendency to crack. Therefore more the hard enable the steel is, the greater is the change of martensite fraction, even at the normal cooling rate, primarily in the HAZ area. A variation in the cooling rate is likely to cause undesirable effects in the weldment.

During the phase transformations of the F.C.C. to the BCC lattice, the free energy is reduced. The enthalpy difference liberated as heat ΔH, result in a slower cooling rate through the transformation change. A variation in the atmosphere and wind velocity etc. can all influence the cooling rate and affects the structure of sensitive material. Cooling rate may also vary during the start and finish of a weld run because of differing initial and final heat flow conditions. A slower cooling rate causes widening of HAZ, i.e., larger volume of metal affected due to heat. In the case of low carbon steel weldment, their crystallization is accomplished within a relatively narrow temperature range, at a rate dependent on the method of welding and application of arcs linear energy. The weldments as opposed to austenitic and purely ferrite one do not retain their initial structure but undergo allotropic transformation.

Voigt et al. [113] investigation shows that the formation of high carbon content martensite and massive iron carbide in the heat-affected zone and partial fusion zone resulted in poor weldability of cast iron. Even after post weld annealing, a fine distribution of secondary graphite particles in the HAZ can prevent the weldment from attaining base metal toughness and ductility.

Groong et al. [114] studied dissimilar welding and the results showed that High-Strength Low-Alloy Steel (A752 grade) normally has low carbon content (around 0.06 wt%C). The final HAZ microstructure contains a fully martensitic microstructure formed upon fast cooling (Dt8/5 < 1.4 s) with a hardness level of ~340 HV while at slower cooling rates (>20 s), coarse bainite (~220 HV) is formed. The grain growth near the fusion line in micro-alloyed steels makes it critical, forming CGHAZ that needs considerable attention as it affects strength. The major parameters which may control the final microstructure evolution of the HAZ are the weld cooling rate, the plate production method and the concentration of the alloying elements in the material [90].

HAZ of Welded 316L Stainless Steel consists of an austenitic matrix for complete solidification shows lesser grain growth as compared to carbon steels. The grain size of the 316L SS base metal is around 20 µm, and the variation highly depends upon processing method (cold rolled/ hot rolled etc.) [115]. As compared to fine-grained carbon steel with smaller grain size, there is a lower driving force for grain growth. In addition, after solidification of joint some delta ferrite may also form at the HAZ grain boundaries suppressing grain growth which ultimately results in a minor hardness increase near the fusion line. However, despite the low susceptibility for grain growth, high HI should be avoided, especially when the base metal has small grains that can cause considerable grain growth in austenitic steels with softening. Due to high heat input and carbon content, there is the formation of chromium carbides on the grain boundaries of austenite, creating a Cr depleted zone around grain boundaries which leads to sensitization, causing a significant reduction in corrosion resistance. Some carbides and nitrides may form along grain boundaries on cooling in the HAZ or at the ferrite–austenite interface, especially if Ti and Nb content are present. These can cause grain boundary liquation by lowering the melting temperature, in addition to the segregation of impurities (primarily P and S), causing liquid films upon cooling. Notably, between the FZ and the HAZ, there is the partially melted zone (PMZ) due to temperature gradients, which has low mechanical properties. Grain growth in this zone is not significant and the grain size is similar to the as-received base metal. **Sabzi et al.** [116] found drastic improvement in mechanical properties and weldability of 316L stainless steel weld by using electromagnetic vibration, thereby limiting the thickness of the UMZ (unmixed zone) to less than <0.5 mm during welding in the GTAW process.

Choubey et al. [117] observed that the HAZ area adjacent to the fusion boundary was coarse-grained HAZ which possessed low hardness whereas the HAZ area adjacent to the base metal was fine-grained HAZ, which possessed high hardness. It is also observed that there is significant grain coarsening in the HAZ of all the joints. Further, it is observed from the optical micrographs that the extent of grain coarsening in the HAZ increases with an increase in heat input.

Dong et al. [118] showed that increasing the heat input restrained the formation of martensite and promoted the transformation of martensite to bainite. When the welding heat input was 0.67 kJ/mm, the microstructure in HAZ was fine lower bainite with some acicular ferrite. In HAZ, upper bainite was produced when the welding heat input was 0.77 kJ/mm, and Vickers hardness of HAZ and Fusion Zone of HSLA steel joints was much higher than that of the parent metal. The average hardness of HAZ decreased with increasing the welding HI.

Sadeghian et al. [119] concluded that the HAZ of the HSLA shows different transformations. Due to thermal cycles, a rapid cooling evolved, which is the case of upper bainite phase. However, the polygonal ferrite and perlite with heterogenic distribution are obtained when the cooling rate is slow.

2.2.6 Heat Treatment of welded joints

Heat treatment is mostly done to remove the residual stresses (called stress relieving) or to disperse the unwanted carbides into the solid solution (called solutionizing) which ultimately improves the mechanical properties.

Pre-heating temperature is defined as “The temperature of the base metal in the volume surrounding the point of welding immediately before welding is started”. Successful welding of materials of high thermal conductivity thick materials or the welding of hardenable steels demand a controlled cooling rate [120]. When these materials are heated to a high temperature (during welding) and cooled rapidly thereafter, they harden. Welding under such conditions without due control of cooling rate may produce embrittlement in HAZ parallel to the weld bead. Preheating reduces the cooling rate; consequently, the metal in and around the weld bead does not harden much. It causes a lesser temperature gradient which would result in a reduction in cooling rate, particularly at temperatures of 800-500°C in which sensitization may occur in Stainless steel (SS). At low ambient temperatures (say at -40°C), the cooling rates will be unusually high, particularly in the dangerous ranges below 800°C for Stainless steel. As the rapid cooling in the range of 315 to 200°C may cause cracks in welds in some HSLA steels [121]. The cooling rate depends upon the geometrical and technological factors like welding process, current, joint restraint and thickness of the component. For low carbon and alloy steel welding, the final microstructure of welded joint can be correlated to the cooling rate from the peak temperature. Welding procedures used for the heat-treatable low alloy steels and chromium-molybdenum steels will normally specify a minimum and maximum requirement for pre-heating and inter-pass temperatures. Low alloy materials can have high hardenability and are susceptible to hydrogen induced cracking. Pre-heating leads to the removal of remaining moisture from the weld area, lowering the thermal gradient, risk of hydrogen-induced cracking and reducing the hardened region of HAZ. Pre-heat can also remove distortion caused due to the shrinkage stress during cooling and normalize the distribution of residual stress.

Post weld heat treatment (PWHT): In PWHT, heat is applied after welding is completed. Post weld treatment is carried out mostly to stress relief the weldment and HAZ. The purpose of stress relieving is to remove any residual or internal stresses that may be present after the welding operation. For some alloy steels, a thermal tempering treatment may provide a suitable metallurgical structure. Extremely coarse weld structures in steel can be refined and hazardous zones in HAZ can be eliminated. This treatment will refine the coarse grain structure and reduce stresses after welding.

Muhammad et al. [122] investigated SS 316L using GMAW in multi-pass welding with PWHT at 1050°C. Also used Potentiodynamic polarization test in a solution composed of H_2SO_4 and 1 N NaCl for $100CO_2$ as shielding gas. The results showed that WM consisted of carbides as black dots, but after PWHT, grain refinement was observed, which improved mechanical properties. From the corrosion test the corrosion rate of as-welded specimen was WM >BM > HAZ, which significantly decreased after PWHT (WM < BM <HAZ).

Nowacki et al. [123] investigated 16 mm butt welded duplex steel for variable heat input in the range of 16-20 kJ/cm for corrosion at 1273K to 1473K for aging duration of 30, 60 to 90 minutes for Post weld heat treatment. Pitting corrosion resistance of the welds is strongly influenced by thermal-cycle parameters and decreased. The mechanism of secondary austenite creation is the diffusive transformation. Similar results were found **Tang** [124] for materials having higher strength had greater susceptibility to corrosion.

Kim et al. [125] investigated hydrogen Embrittlement on HSLA steel in as welded and post weld heat treatment at 550°C for 720 hr and studied corrosion resistance and mechanical properties from an electrochemical view. Corrosion resistance and mechanical properties were also increased by post-weld heat treatment and an increase in susceptibility to hydrogen Embrittlemen was observed. Fracture morphology indicated a ductile mode of fracture in both as-welded and post-welded conditions.

Mohandas et al. [126] Welded High Strength Low Alloy in Ar as purging gas using GTAW and GMAW followed by post-weld heat treatment at 900°C for 30 minutes. It was found that steel with a high carbon equivalent exhibited maximum HAZ softening in GTAW and GMAW and concluded that HAZ should be not more than half of the plate thickness. Steel with longer critical cooling time exhibited more resistance to softening in GMAW, and heat treatment in austenitic zone can eliminate the softened zone. Copper backing and argon purging reduced the tendency for softening in HAZ in mild steel.

2.2.7 Optimization in welding

Optimization is a process of making things from better to best. It is a process of selecting inputs called as independent variables, which affect the overall quality in terms of strength, ease of working, uniformity across the weld called output variables that are chosen for the minimum or maximum output. The inputs are the variables, and the process or function is called objective function. When only one objective function is involved in the problem, it is called single-objective optimization. But in reality, in most real world problems, more than one objective function is required to be optimized, named multi-objective optimization.

Vasiljevi [127] classified methods to solve optimization problems into two major categories viz., classical and evolutionary methods. In a classical approach, the optimal solution is obtained from a single random solution which is updated in every iteration by deterministic procedure. Again this method is subdivided into two categories viz., direct method and gradient method. While in an evolutionary approach, the system mimics the evolution principle of nature which results in a search and optimization algorithm.

Taguchi Technique: Generally, due to complex nature of traditional designs of experiments, these are often used in real-time problems. But in industry, it is desired to determine the exact values of the process input at which their output reaches their optimum value. The optimum could be minimum, maximum of a particular function or close to a normal distribution curve in terms of the process input parameters. In order to describe the output performance of the welding process and find the optimum of the responses of interest, many researchers prefer Taguchi optimization techniques. Taguchi optimization technique is a powerful tool for the design of high-quality experimental design systems. It acts as a simple, efficient and systematic approach to optimize designs for performance, quality, and cost. The methodology is valuable when the design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system performance to sources of variation. In recent years, the rapid growth of interest in the Taguchi method has led to numerous applications of the method globally in various industries. Taguchi method can be used to Engineering problems of optimization and can be carried out in a quick time with the help of software like Matlab, Minitab etc., which execute analysis and has further eased the data analysis in an economical way. Through the application of Taguchi's technique, we can yield better results in lesser time economically.

Ghosh et al. [128] worked on parametric optimization of GMAW Welding of 316L steel by Grey-Based Taguchi method and successfully optimized it. Chosen variables were current (100, 112 and 124 A), nozzle to plate distance (9, 12 and 15 mm) and gas flow rate of (10, 15 and 20 l/min). Used L_9 Taguchi orthogonal array of DOE and so performed 9 experiments and analyzed the yield strength, ultimate tensile strength and percentage elongation as output. It was found that current was the most influential parameter, followed by weld speed and voltage, which affect the weld strength. Optimum welding parameters were current of 100 A, gas flow rate of 20 l/min gas and nozzle to plate distance of 15 mm.

Similarly, **Ghosh et al.** [129] optimized GMAW parameters using grey relational method for 409 ferritic stainless steel for UTS and percentage elongation. Used 3 levels of current (100, 112 and 124 A), gas flow rate (10, 15 and 20 l/min) and nozzle to plate distance (9, 12 and 15 mm) and ANOVA analysis which tells the percentage contribution of process parameters on mechanical properties. The optimum welding parameters found were current of 124 A, gas flow rate of 10 l/min and nozzle to plate distance of 9 mm.

Patil et al. [130] optimized the parameters of GTA welding on SS 304 on the basis of the tensile strength and hardness. They varied the root gap, filler diameter, welding current, gas flow rate, plate thickness and electrode diameter and performed 22 experiments. On the basis of the DOE, maximum tensile strength was 618.72 MPa, and maximum hardness was 87.92 HRB at a root gap of 2.83 mm, filler rod diameter was 1.76 mm, welding current was 140 A, plate thickness was 5.48 mm, electrode diameter was 3.2 mm, and the gas flow rate was 11.92 l/min.

Chauhan et al. [131] optimized the process parameters of MIG welding for welding of stainless steel SS 304 and low carbon steel. They varied the three process parameters at three levels which are welding current (80, 100 and 120 A), welding voltage (16, 19 and 22 V) and welding speed (30, 40 and 50 cm/min). They analyzed the UTS and optimized the process parameters. They also applied the ANOVA which tells how much significant the process is and the percentage contribution of process parameters on ultimate tensile strength. The effect of welding current on the UTS is more, followed by welding speed and voltage. Similar results were found by **Arya et al.** [132], who optimized the process and varied 5 process parameters at 4 levels using L_{16} Taguchi orthogonal.

Sudhir et al. [133] optimized the welding parameters for MS 1018 steel for MIG With Grey based Taguchi method with variable Preheat Temperature: 275-300°C, Current: 75 to 120 A and Voltage: 25 to 35 V for joint efficiency, UTS and percentage elongation. Found optimal parameters were: Preheat of 275°C, current: 120 A and voltage: 35 V. Pre-heat temperature followed by current and voltage was the most influential among the chosen parameter. The optimum parameter resulted in joint efficiency of 94.37%. UTS and percentage elongation of welds decreased on increasing the pre-heat temperature, on the other hand, they increased on increasing the current.

By applying the Taguchi's results, the quality of the joint can be improved to get the desired properties. A special design of orthogonal arrays are used to solve a problem and study the entire parameter space with a smaller number of experiments. The experimental results are then transformed into a signal-to-noise (S/N) ratio that shows the variability. This approach takes care of both static and dynamic problems in industry. As in a static response experiment, the quality characteristic of interest has a fixed level, while in a dynamic response experiment, the quality characteristic operates over a range of values, and the goal is to improve the relationship between an input signal and an output response.

2.2.8 Observation from literature review/ Research gap

It is observed from the literature review that different combinations of welding process parameters have been varied for study. In most of the literature, welding current, gas flow rate, travel speed voltage, wire feed rate, nozzle to plate distance and electrode diameter are varied but few have discussed the specific contribution in attaining the optimum joint properties that need special attention. No clear investigations have been carried out on HAZ as a criteria for the weld strength of A572 gr. 50 and 316L stainless steel joints. Fewer investigations have been carried out to assess the effects of pre-mixed shielding gas (Ar and CO_2) on HAZ. GMAW Welding has not been explored exclusively for welding of A572 gr. 50 and 316L SS alloy in terms of different welding parameters for Heat Affected Zone behaviour. DOE using Taguchi approach can significantly reduce the number of experiments required and makes experimentation economical for expensive materials.

The experimental work would involve the primary stage, which includes experimentation using DOE using Taguchi's approach for optimization and selection of levels for welding current, shielding gas flow rate and weld speed. The secondary stage involves the investigation and validation of results in terms of mechanical and metallurgical properties for the welded joints with a prime focus on HAZ. In the experimentation part, welding parameters Arc Voltage, Welding Current and gas flow rate will be altered suitably, and their effect on microstructural and mechanical properties which include Optical Microscopy, Scanning Electron Microscopy, Hardness, Ultimate Tensile Strength and Yield Strength will be investigated.

2.2.9 Aim and Objectives of the present work

Present work aims to fabricate A572 gr. 50 and 316L SS welded joint using GMAW welding at variable current, weld speed and gas flow rate under protective shielding gas mixture of Argon and Carbon dioxide. The pre-mixed gas mixture of Ar and CO_2 will be used as shielding gas for the fabrication of joints with the aim to find the optimum parameters of welding and their effect on Heat Affected Zone (HAZ) behaviour. DOE using Taguchi’s approach will be used to quantify and study the effect of welding parameters, especially on HAZ and find the parameters that can improve the quality of weld and reliability. It will also be used to find the relationship between the variable parameters and HAZ. Further, the results will be verified again through techniques like microstructural, fractographic and mechanical properties study to validate the results.