

# **Chapter 1**

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## **Introduction**

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This chapter gives a general introduction on Welding and Heat Affected Zone in steels and its effect on joint properties. Major points discussed includes,

- Welding techniques
- Gas Metal Arc Welding (GMAW) and Heat Affected Zone (HAZ) generation in welding
- Classification of HAZ zones
- HAZ as a critical area in welded joint
- Applications

The introductory chapter concludes with a detailed investigation of Gas Metal Arc Welding (GMAW) and Heat Affected Zone (HAZ) as a critical area prone to defects and discontinuities.

## 1.1 Introduction

Welding technology is a significant part of any mechanical fabrication facility in the world. It's considered the most widespread metal joining process in industries. Out of mechanical fastening, adhesive bonding and welding process, only welding can provide 100% joint efficiency [1, 2]. In a welding process, two or more materials are fused together to form a weldment after solidification. The fusion may or may not require the application of heat energy, pressure or both. Referring to the “Welding Hand-book, 1987” published by the American Welding Society (AWS), it is comprehended that welding is a location-specific coalescence of materials. Welding processes are distinguished by the way metals are joined or the mode through which the metals are melted. If heat is generated using an electric arc, then it is called Arc Welding, e.g. Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Gas Metal Arc Welding (GMAW), Tungsten Inert Gas (TIG) welding and these are the most commonly used welding methods nowadays. Along with electricity, if pressure is also used during welding, it is called as Resistance Welding (like spot welding, seam welding and projection welding). Welding can be classified as shown in Figure 1.1[3].

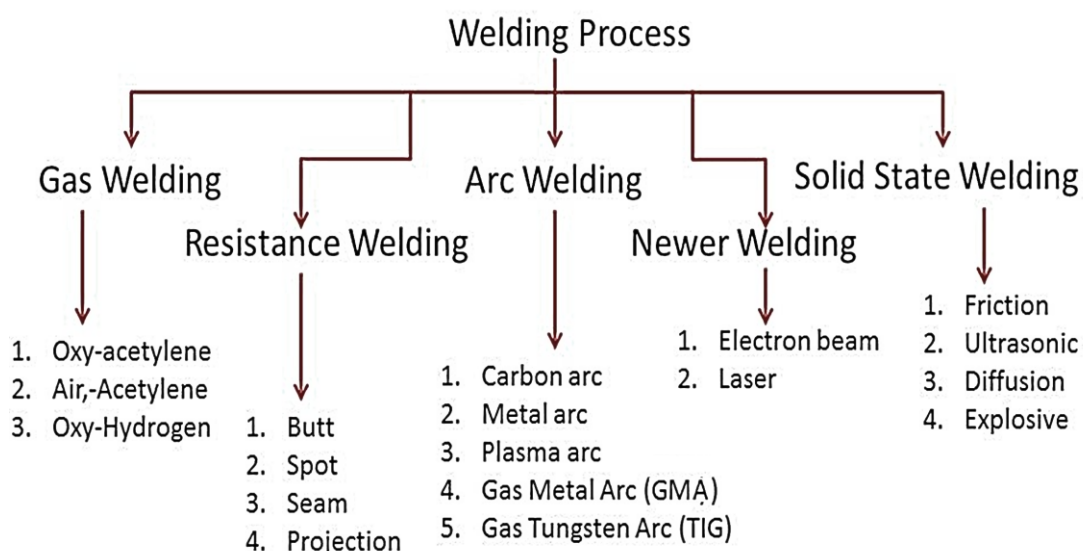


Figure 1.1: Classification of welding process. Reproduced with permission from Ref. [3]. Copyright (2020) Tri-State Fabricators

Among the welding processes, Arc welding is widely used for strong and reliable joints. Among the arc welding processes, Metal Inert Gas (MIG) welding process has been preferred for long and continuous joints, especially for structural joints, bigger vessels and massive structures. An arc welding process performed using an inert gas like Argon (Ar) or Helium (He) as shielding gas is called as MIG welding, while arc welding under an active gas (like Carbon dioxide) is called as Metal Active Gas (MAG) welding [4]. MIG welding was initially developed for the welding of non-ferrous materials, but the introduction of CO<sub>2</sub> as shielding gas boosted its industrial use with demerits of higher spatter quantity, porosity and poor surface appearance. At the same time, the use of a gas mixture of argon and carbon dioxide has improved the quality of joints drastically.

## **1.2 Arc Welding Processes**

The AWS defines Arc welding as “A process that uses an electric arc as a source of heat to melt and join metals”. In an arc welding process, heat for fusion is generated by the electric arc between filler metal/electrode and the base material in a protective environment, developing a temperature over 5000°C in a localized area [5]. Among arc welding processes, GMAW and TIG welding are widely used in the industries for quality welds. TIG welding produces high-quality welds, but it cannot be used for long and continuous welds. The Gas Metal Arc Welding (GMAW) process is an arc welding process which produces the coalescence of metals by heating them with an arc between a continuously fed electrode (filler metal) and workpiece under a protective environment that provides the benefits of a long and continuous weld. GMAW can be used in 4 modes (Short-circuit metal transfer, Globular metal transfer, Spray metal transfer and Pulsed current transfer mode) for ferrous and non-ferrous material of wide thickness ranges. The advantage of high productivity and relatively low heat input to the workpiece, along with ease of automation, make it one of the favourites with respect to other welding processes.

Productivity is considerably higher as there is no need to interrupt welding to replace filler rods, and little or no slag removal is required as in Manual Metal Arc Welding (MMAW)/ Submerged Arc Welding (SAW). It is a pretty flexible method and long, continuous and high-quality welding can be done in all positions at high welding speeds [6]. A lower level of spatters along with a high deposition rate can be achieved. A skilled operator is not necessarily required as compared to other welding processes. All common structural materials, such as mild, low-alloy, stainless steel, aluminium and its alloys can be welded. Even Surface coated metals can also be welded.

### **1.3 Heat Affected Zone Generation in Welding**

During a manual welding operation, the welder needs to have control over the welding parameters for defect-free weld joint along with full penetration. Weld control ultimately affects the yield strength, ultimate tensile strength, percentage elongation, penetration, bead geometry, Heat Affected Zone size and the overall weld quality. Welded joints can be broadly classified into three zones, namely Fusion zone (FZ), Heat Affected Zone (HAZ) and Unaffected Zone (UZ) i.e. the base material (BM). FZ accommodates re-solidified base material or a combination of filler and base material. The strength and properties of this zone strongly depend upon the characteristics of base material, filler material and heat imparted during welding procedure i.e. Heat Input (HI). The parameters that dictate the microstructural changes are the amount of heat input, peak temperature, and total duration of elevated temperature and the cooling rate of a weld. The total heat generated during arcing is wasted through radiation (in the form of light), convection (through shielding gas) and conduction (through base metal), as shown in Figure 1.2. Conduction causes the excessive heating of material away from the weld pool and alters its properties creating HAZ. Also, the capability of materials to transfer the heat variations rapidly to the surroundings and cool quickly dictates the HAZ width.

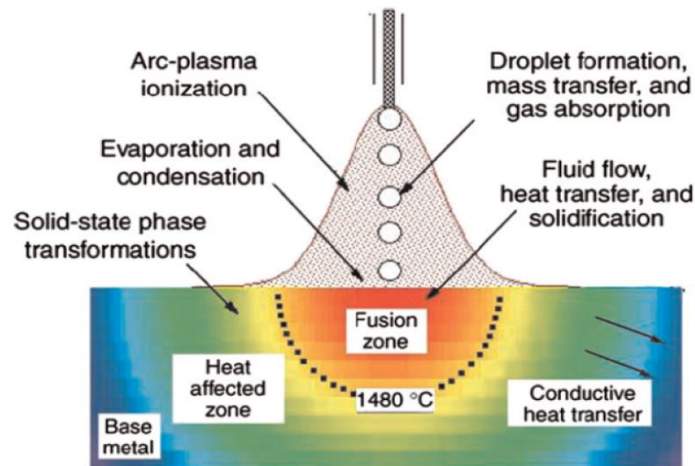


Figure 1.2: Schematic diagram of the interaction of heat source with metal and regions of the weld. Reproduced with permission from Ref. [7] Copyright (2018) Elsevier

Thermal diffusivity of material influences the size of the HAZ, which depends upon the metal's thermal conductivity, density, specific heat and heat input during welding. As the weld metal goes through, a solid to liquid (during arcing) and then again liquid to solid-state transformation resulting in microstructural change and properties. HAZ goes through solid-state transformations only. In addition to phase transformation, grain growth, precipitations, coarsening, and solute redistribution must be considered to find the resulting weld properties. The transformations involve phase changes in diffusional processes, solid-state processes involving grain growth, phase changes involving displacement transformation and phase changes such as spinodal decompositions (SD). SD is a mechanism by which a single thermodynamic phase spontaneously (i.e., without nucleation) separates into two phases [7, 8].

HAZ zone is the base material heated to a temperature up to solidus resulting in varying degrees of influence on microstructure as a consequence of the heating and cooling cycle. Stress variation caused during welding and solidification of weld bead is beard by HAZ. The heating and cooling cycle induce stresses and create heterogeneous microstructure across the weld bead and sometimes cracks too (Hot/Cold cracks) if correct parameters or preventive measures to avoid cracking are not taken. Those materials, which do not undergo a solid-state phase transformation during cooling, a grain

growth zone and a recrystallized zone exist. The various HAZ areas having a series of visible coloured bands caused by surface oxidation indicates (approximate) the temperature attained in HAZ near a weld in steels, as shown in Figure 1.3 [9]. However, weld parameters are not entirely independent and changing one variable generally requires a change in some of the others to achieve the desired results.

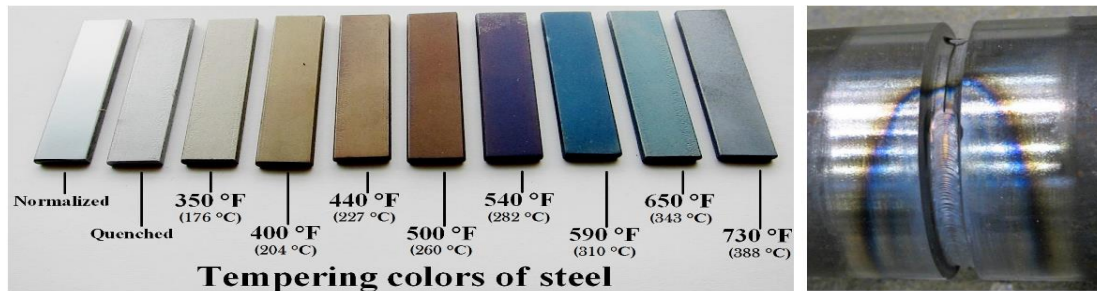


Figure 1.3: Tempering colours of steel due to heat. Reproduced with permission from Ref. [9] Copyright (2012) Gasparini Industries S.R.L.

When all the parameters are in proper balance or optimum, the welder can deposit higher quality weld metal and produce sound welds. The automated GMAW setup minimizes the discontinuous bead profile and variable bead shape, and other defects. Highly skilled labour is required in manual welding, while in automated GMAW machines, less skilled labour can easily optimize the parameters and weld a satisfactory weld joint. The selection of the welding variables should be made after the base metal, filler metal, and joint design have been determined. So it becomes necessary to choose the parameters carefully. Optimum welding parameters will increase the chances of producing welds of a satisfactory quality just after welding and during the service life of the weld joint.

#### 1.4 Arc Welding Process Variables

Process variables contribute in dictating the total heat imparted to the workpiece and filler electrode during welding and affect the yield strength, ultimate tensile strength, percentage elongation and deposition rate. Arc welding process variables can be broadly subdivided as Primary welding variables and Secondary welding variables as follows:

### **1.4.1 Primary Variables**

The welding current, voltage and welding speed are most commonly used to change the characteristics of the HAZ and weld metal are thus called primary variables.

Welding current dictates the HI during welding and controls the electrode burn-off rate, the dilution, penetration, the geometry of the weldments and heat available to form HAZ. As current is proportional to HI, its increase will increase HAZ width and control the dissolution of precipitates. In a constant voltage system, the wire feed speed increases with the welding current causing an increase in wire melt-off rate and deposition rate. Very low welding current produces a poor penetration weld, while at a very high current, weld bead size is large and may cause burn-through and undercut. Welding voltage determines the shape of the fusion zone and reinforcement. Maximum penetration is obtained at an optimum arc voltage while Lower voltage produces wider, flatter and shallow penetration welds. For example, the normal arc voltage in CO<sub>2</sub> and He is much higher than those obtained in Ar as shielding gas. If all other parameters are constant, the arc length directly depends on the arc voltage. A long arc length disturbs the gas shield, and the arc tends to wander and thus causes the formation of excessive spatter and porosity. Welding speed is the rate of welding torch movement along the workpiece. HI can be decreased by increasing welding speed causing narrower HAZ and a decrease in the weld reinforcement. In semiautomatic welding, the welder controls it, while in automatic welding, the machine acts as the controller. At constant current, low travel speeds proportionally provide larger beads and larger HAZ due to reduction in cooling rate around weld. The high Heat Input increases the HAZ width and weld penetration and a wider bead contour. At too low weld speed, unusual weld build-up occurs, which causes poor fusion. Excessively high speeds result in humping beads, high spatter and undercuts often creating the need for another pass. Number of passes increases the metal deposition

in the weld groove and increases the weld reinforcement. An increase in the number of passes causes excessive heat generation and alteration in microstructure with an increase in martensite composition and mechanical properties, especially in HAZ. Re-heat cracks may also appear in multi-pass welding. Subsequent passes act as preheating medium for the next pass and reheats.

### **1.4.2 Secondary Variables**

Electrode Diameter directly influences the penetration, bead reinforcement and bead width, consequently affecting the speed of welding. As for the same welding current, the arc becomes more penetrating with a decrease in electrode diameter while a large diameter electrode requires higher minimum current. To maximize deposition rate, the smallest wire possible that provides the required penetration is recommended at a given current. Small diameter wires are suitable for thin sections and welding in vertical and overhead positions. Large diameter wires are desirable for heavy sections, and hard surfacing and built-up works with low current applications because of less weld penetration. Electrode inclination is the angle which the electrode makes with the normal at the arc point in the longitudinal plane. The torch maintained perpendicular to the joint is called normal. When the electrode is pointed in the direction of advance, it is said to be forehand, while if it is pointed in the opposite direction, it is said to be backhand. Electrode angle of 7-15° in the direction of advance is recommended in GMAW.

Shielding Gas: The choice of shielding gas depends on the working metals and affects the welding cost, weld temperature, arc stability, weld speed and spatter levels. It also affects the weld penetration, depth, surface profile, porosity, corrosion resistance, strength, hardness and brittleness of the weld material. Surface oxidation, low penetration and carbon absorption can be prevented using the right combination of shielding. Argon (Ar) provides lesser penetration with respect to helium. Argon generally provides a

smooth and quieter arc and proves more economical than helium. For these reasons, Ar is preferred for most applications and materials, including metals of larger thicknesses and high thermal conductivity. Ar is less used for materials having high heat and penetration requirements for welding. Aluminium and copper are metals of high heat conductivity and are examples of such types of materials for which helium is advantageous in welding. Pure Ar can be used to weld structural steels, low alloyed steels, stainless steels, aluminium, copper, titanium and magnesium. The Ar-H<sub>2</sub> mixture is used for welding a few grades of stainless steel and nickel alloys. He-Ar mixtures may be used for low alloy steels, aluminium and copper. Ar mixture with CO<sub>2</sub> has improved the weld penetration and lowered the spatter levels.

### **1.5 Optimization of Process Parameters of Welded Joints**

Process parameters play an important role in the production of a quality weld in a single step without rejection. So it becomes necessary to find the optimum parametric levels/condition for welding a particular material. As conducting trials for optimum welding parameters is a time-consuming and costly process, it becomes necessary to adopt ways to minimize the number of trials. Hence Design of Experiment (DOE) models can be used to reduce the overall cost of welding by reducing the number of trials and makes it user-friendly for industrial environments [10]. The investigated model should be simple and provide precise information, like the optimum process parameters, parameters that need special attention during welding and their overall contribution to the quality weld. The optimization tool used in the thesis deals with the input parameters of GMA welding and examines the interaction between welding parameters and their response. Through DOE analysis using Taguchi's approach, 3-factors and 4-levels of input parameters were investigated for joint strength and behaviour of HAZ. Primary variables are the most important factors to control welding quality, productivity and

failure cost. The Experiments were conducted based on Taguchi for higher strength. The experimental work was conducted to optimize the input process parameters to get optimum welding quality. By conducting DOE, we can find the contribution made by each chosen welding parameter for optimum strength. Analysis and optimization of GMAW welding parameters were conducted based on ANOVA, and obtained interaction plots were validated through the microstructure and mechanical properties.

## **1.6 GMAW application for welding Steels**

Structural steels are widely welded using GMAW/MIG process ranging from in-house equipment to industrial boilers and bridges. Steel is one of the most popular materials for structural and engineering components if corrosion is least concerned. While for corrosive environments, Stainless Steel or non-ferrous metals are the preferred choices. Steels can be broadly classified by a variety of different systems like the composition (carbon, low-alloy or stainless steels), manufacturing method (open hearth, basic oxygen process, or electric furnace methods), the strength levels required (like high strength low alloy steels), finishing method (hot rolling or cold rolling) and the microstructure (ferritic, pearlitic and martensitic) etc. Failure in welded joints after a longer duration of service life is mostly due to loss of alloying elements, pre-existing micro-cracks or stresses causing corrosion (mostly around HAZ). For structural materials, weldability and strength levels are of great concern. Normally High Strength Low Alloy steels (HSLA) steels or micro-alloyed steels are designed to provide good weldability along with better mechanical properties and/or higher resistance to atmospheric corrosion than conventional carbon steels. They are designed to meet specific mechanical properties rather than a chemical composition.

**A572 gr. 50** is readily available and exhibits excellent physical and mechanical properties, and is the best replacement for commercially viable mild steel with the added

value of high strength and better corrosion resistance. Low carbon percentage makes it less susceptible to cracking and have good weldability ( $C_{eq} < 0.42\%$ . if carbon is less than 0.12%, then  $C_{eq}$  can be tolerated up to 0.45%), and defects often occur if care is not taken during fabrication. Using higher-strength steel can enable substantial savings in structural weight and material costs.

From Figure 1.4, we can see that HSLA steels are widely used in the automobile sector, containing a share of 25%. A typical application of A572 steel includes Alexandra Bridge by Tsai project, steel lightning poles and various pipe welds etc. Failures in HAZ have also been found, as shown in Figure 1.5. Thermal stresses, segregation of low melting solids (like sulphur and phosphorus) and inclusions in the HAZ region might be the possible causes, and these can be reduced if optimum welding parameters were used.

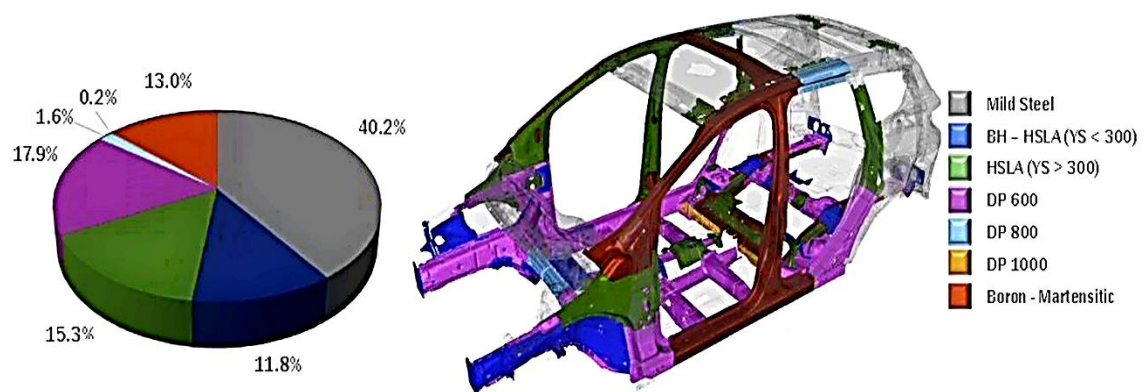


Figure 1.4: Application of HSLA in automobile. Reproduced with permission from Ref. [11] Copyright (2020) Skill-Lync Inc.



Material failure in HAZ\*      HAZ of a fillet weld\*\*      HAZ failure outside weld bead\*\*  
 Figure 1.5: Weld failures in HAZ [7, 8] Reproduced with permission from Ref. [12, 13] Copyright (2019) ProQuest LLC

**Stainless Steels** are another category of steel that defies most of the hazardous environmental conditions. Strength, formability, corrosion resistance and good

crashworthiness makes stainless steel versatile enough to be used as a structural component. Typical applications include domestic, industrial (storage equipment, aircraft parts like exhaust systems, turbo-superchargers, and gas turbines), transport, architectural products, petroleum industries (refinery equipment) etc. Also, the medical devices, pipe works, tanks, chemical processing vessels for aggressive corrosive liquids, pulp and paper vessels and marine environments, especially those with chlorides uses.

Among stainless steels, 3XXX series of Austenitic type stainless steels are widely used up to 63%, followed by series 4XXX(24.8%), 2XXX(9.8%) and duplex(0.6%) [14]. In 3XXX series, 316L has the widest application after 304L steel. The low carbon version of 316 stainless steel is 316L which is best for highly corrosive environments. A 316L SS welded boat hull weld joint is shown in Figure 1.6(a).

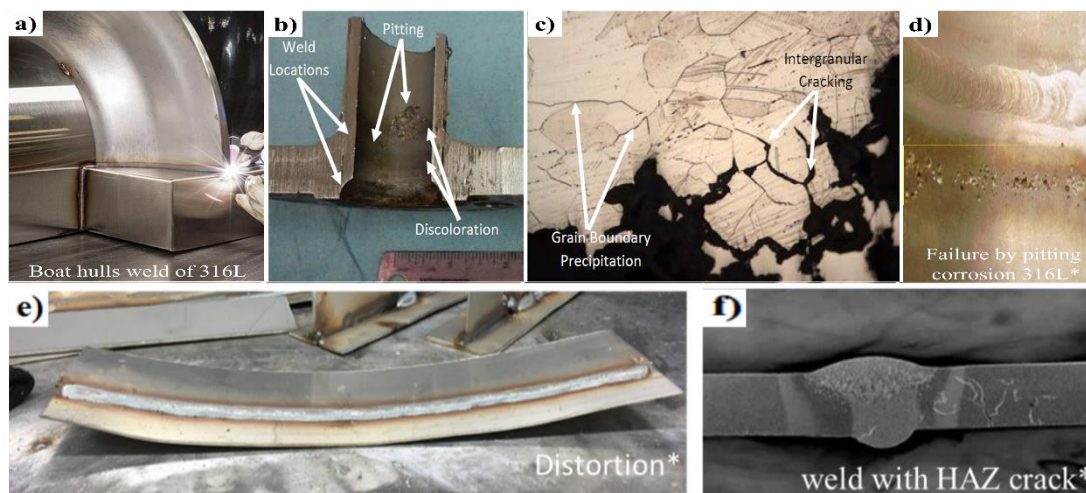


Figure 1.6: Application of 316L SS in a) Boat hulls, b) Discolouration, c) Intergranular cracking, d) Pitting, e) Distortion, f) Failure in HAZ. [15, 16] Copyright (2020) Weldinganswers.com

Type 316L SS alloy contains molybdenum (Mo), and it has a greater resistance to chemical attack than other stainless steel grades. 316L has considerably more resistant to solutions of sulfuric acid, chlorides, bromides, iodides and fatty acids at high temperatures. Stainless steel weld joints exhibit lower penetration, high levels of spatter generation, segregation of alloying elements (In HAZ) and welding cracks if welding conditions are not optimum, as shown in Figure 1.6(b-f). Matching or over alloyed filler

wire is generally used for uniform hardness, avoid loss of elements during welding, and maintain uniformity in metallurgical properties.

So during the investigation, commonly used and available steel plates A572 gr.50 and 316L SS were considered as the workpiece material for welding purposes.

### **1.7 Characteristics of A572 and Stainless Steels**

A572 steel is a micro-alloyed/ High Strength Low Alloy (HSLA) steel. These are similar to as-rolled mild steel with enhanced mechanical properties obtained by adding small amounts of Cr, V, Mo etc. alloys. Special processing techniques such as controlled rolling and accelerated cooling methods are used for improved properties. The HSLA steels have low carbon contents (0.03-0.25% C), and to produce adequate formability and weldability, and they have manganese contents up to 2.0%. Small quantities of Cr, Ni, Mo, Cu, N, V, Nb, Ti and Zr are used in various combinations to gain better properties through grain refinement [17]. HSLA steels include weathering steels that contain small amounts of Cu and P, providing improved atmospheric corrosion resistance through solid-solution strengthening. Microalloyed ferrite-pearlite steels have very small (<0.10%) additions of strong carbide or carbonitride forming elements such as Nb, V, and/or Ti for precipitation strengthening and grain refinement. As-rolled pearlitic steels include carbon-manganese steels tailored with alloying elements to enhance strength, toughness, formability and weldability. Acicular ferrite steels have low-carbon (<0.05% C) with an excellent combination of high yield strengths (as high as 690 MPa), weldability, formability, and good toughness. Dual-phase steels have a microstructure of martensite dispersed in a ferritic matrix and exhibit high ductility and tensile strength. Inclusion-shape-controlled steels provide improved ductility and through-thickness toughness by the small additions of Ca, Zr, or Ti. Due to these rare earth elements, the shape of the sulfide inclusions transforms from elongated stringers to small, dispersed,

almost spherical globules [18].

**Stainless steels** contain alloying elements like chromium (at least 10.5%), Nickel, Molybdenum etc. and are classified into five main types as follows:

Austenitic stainless steels are 200 and 300 series steel with high corrosion resistance and high formability but are prone to stress cracking. These are considered to have very good weldability. These exhibit good toughness because they are non-hardenable on cooling, and there is no need for pre or post-weld heat treatment. 316L stainless steel falls in this category and are normally welded with fillers with matching composition to base material. In specific cases, type 308 filler is used for 302 and 304 alloys. Type 347 filler is used for 321. Ferritic stainless steels are 400 series, having lower ductility and lower corrosion resistance than the austenitic grades. These offer high resistance to stress corrosion cracking. These have poor weldability when compared to the austenitic stainless steels, as the brittleness and poor ductility of these materials limits their applications in the welded condition. Ferritic stainless steels become fully ferritic at high temperatures and undergo rapid grain growth, which leads to brittle HAZ in the fabricated product. Martensitic stainless steels are 400 and 500 series having higher strength, wear resistance and fatigue resistance than the austenitic and ferritic grades but a lower corrosion resistance. Martensitic steel becomes hard and brittle upon cooling, making it a great material for wear resistance but more difficult to weld as it has weld cracking tendency on cooling in the heat affected zone. Precipitation-hardening stainless steels contain both Cr and Ni that provide an optimum combination of high strength and corrosion resistance. These steels are known for their ability to acquire high strength through heat treatment while possessing the corrosion resistance of austenitic grades and welded through austenitic filler rods. Duplex stainless steels are two-phase microstructure consisting of gains of both ferritic and austenitic stainless steel. These exhibit

significantly better toughness and ductility than ferritic grades but lower than values of austenitic grades [19].

### **1.8 Differences between A572 gr. 50 steel and 316L Stainless steel:**

Common differences between A572 gr. 50 steel and 316L Stainless steel are:

- 316L is known as 18/10 stainless steel. Whereas A572 gr. 50 steel is known as structural steel/ HSLA steel.
- In 316L, the presence of Cr makes it corrosion-resistant, whereas there is very little Cr in A572 gr. 50. Still, A572 is more resistant than mild steel and to protect it from further corrosion, a galvanizing layer is required.
- The microstructure of A572 shows approximately 75% ferrite and 25% pearlite, while  $\delta$ -ferrite traces in austenite matrix is found in 316L stainless steel.
- A572 grade contains carbon between 0.05-0.25% as their main constituent, while 316L SS has min. 16% Cr, 11% Ni and 2.5% Mo by weight with other alloys.
- The strength of A572 gr. 50 (UTS~395 MPa) steel depends upon the carbon component and processing method, whereas 316L is a higher strength material (UTS~520 MPa) and strength depends upon the alloy concentration.
- A572 gr. 50 steel is magnetic, while 316L Stainless steel is not magnetic.
- A572 is a low-cost grade comparatively with 316L SS, which is a preferred material for medical equipment, food processing units, vessels etc.

### **1.9 Motivation/ Need for the research work**

Heat Affected Zone acts as a critical area and experiences a considerable amount of heat and stresses along with the weld pool. Due to uneven heating and cooling cycles during welding, excessive heat and stress are experienced. Its microstructure and mechanical properties become different from the base material and create inhomogeneity in metallurgical structure. The inhomogeneity of microstructure across the weld joint may cause stress concentration and induce stresses. Induced stresses are undesirable and may result in uneven strength levels, increased cracking susceptibility, reduced corrosion resistance and toughness. As a result of this, the HAZ is often an area where failures can occur. Base material in front of weld pool experiences tensile stress while the rear side experiences compressive stress, and due to repeated change of stresses, weld joints are

prone to defects, as shown in Figure 1.7 [20]. Also, the reduction in corrosion resistance is a common side-effect of the high temperatures experienced by HAZ in stainless steel.

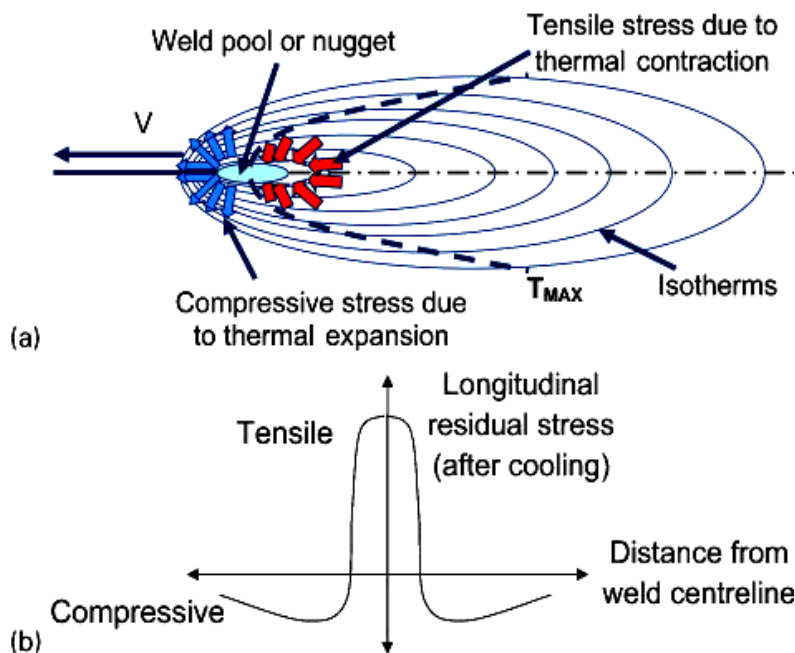


Figure 1.7: Stress development a) During welding, b) After welding (Longitudinal).  
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The weld heat causes chromium carbides to precipitate around the grain boundaries and reduces Cr content below 10.5 % in HAZ, so it loses its ability to form a passive film and corrosion resistance. This results in intergranular corrosion, also known as sensitization or weld decay. In conventional steels, hydrogen embrittlement is another undesirable side-effect of the high temperatures, where hydrogen trapped in the cooling weld bead is rejected into the transforming HAZ. The hydrogen diffuses to the region of highest strain (usually the weld toes or HAZ), creating additional pressure within the lattice and potentially causing cracking. The harder HAZ than base material can bring challenges in the design and use of components. Choosing the optimum parameters followed by heat treatment may reduce the HAZ size and stress levels [21]. The heat treatments like precipitation hardening treatment or solutionizing can provide desired properties. However, these processes can be tedious and impractical with larger structures like bridges and supply vessels with a lot of time wastage and may not offer a total solution.

Finally, the oxidized heat tint indicates the loss of alloying elements in HAZ, creating a Cr depleted zone that weakens the part. So HAZ should be minimized by selecting the correct /optimum welding parameters for the particular material.

The arc generated in GMAW provides sufficient heat energy for changing properties of weld bead and un-melted base metal, i.e. HAZ. Heating cycles in welding leads to variation in weld joint strength, so it becomes essential to analyze the effect of microstructural changes on the strength of the welded joint and find the optimum parameters for welding. Emphasis has been given to the HAZ and welding process parameters giving favourable microstructure and optimum joint strength with a minimum width of HAZ. Weld parameters not only dictate the peak temperature during welding but also predict the shape, size and strength levels of weld bead and HAZ. Micro alloyed and stainless steels designed for specific properties (strength, toughness or corrosion resistance) becomes more sensitive to heat input and the welding parameters due to which the acceptance range becomes very narrow.