PARAMETRIC INVESTIGATION OF INDUCED OSCILLATION ON ARC WELDING

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Nomenclature

$\boldsymbol{V_A}$ = Vibration amplitude

$\boldsymbol{V_F}$ = Vibration frequency

$\boldsymbol{W_S}$ = Welding speed

$\boldsymbol{E_A}$ = Electrode angle

VAW = Vibration assisted welding

Abstract

Welding is one of the important processes in mechanical engineering. In engineering sector, welding is a common phenomenon. Now-a-days, production time is an important factor in industrial sector because every industries is very competitive with each other. At the same time, maintaining quality of the product is necessary. For maintaining quality of joining process, there must be some changes in regular welding process. Normally, regular welding consumes lots of time. According to the research in welding process, it has been found that oscillation can improve mechanical properties of the joining section. However, welding joint quality varies with different ranges of parameters in different conditions. This study has been performed to analyze those ranges of parameters in some selected conditions. Here are some input parameters like vibration amplitude, vibration frequency, welding speed and electrode angle are selected to analyze the variation in welded joint. For analyzing the results, output parameters – hardness, bending strength, deposition rate and dilution are calculated. It has been found that if all input parameters are kept in a selected range then output parameters – hardness, bending strength, deposition rate and dilution increase than regular case. Therefore, it can be seen that welding process assisted by oscillation increases production rate as well as quality in high welding speed. After all, oscillation affects all of the major mechanical properties, which gives strength to the joining section in a welding process.

Chapter 1 Introduction

A weld is made when separate pieces of material to be joined combine and form one piece when heated to a temperature high enough to cause softening or melting. Filler material is typically added to strengthen the joint. Welding is a dependable, efficient and economic method for permanently joining similar metals. In other words, you can weld steel to steel or aluminum to aluminum, but you cannot weld steel to aluminum using traditional welding processes. Welding is used extensively in all sectors or manufacturing, from earth moving equipment to the aerospace industry.

1.1 Welding Processes

The number of different welding processes has grown in recent years. These processes differ greatly in the manner in which heat and pressure (when used) are applied, and in the type of equipment used. There are currently over 50 different types of welding processes; but three types of electric arc welding, which is the most common form of welding. The most popular processes are shielded metal arc welding (SMAW), gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). All of these methods employ an electric power supply to create an arc, which melts the base metal(s) to form a molten pool. The filler wire is then either added automatically (GMAW) or manually (SMAW & GTAW) and the molten pool is allowed to cool. Finally, all of these methods use some type of flux or gas to create an inert environment in which the molten pool can solidify without oxidizing.

1.1.1 Shielded Metal Arc Welding (SMAW)

SMAW is a welding process (Figure 1.1) that uses a flux covered metal electrode to carry an electrical current. The current forms an arc that jumps a gap from the end of the electrode to the work. The electric arc creates enough heat to melt both the electrode and the base material(s). Molten metal from the electrode travels across the arc to the molten pool of base metal where they mix together. As the arc moves away, the mixture of molten metals solidifies and becomes one piece. The molten pool of metal is surrounded and protected by a fume cloud and a covering of slag produced as the coating of the electrode burns or vaporizes. Due to the appearance of the electrodes, SMAW is commonly known as 'stick' welding.

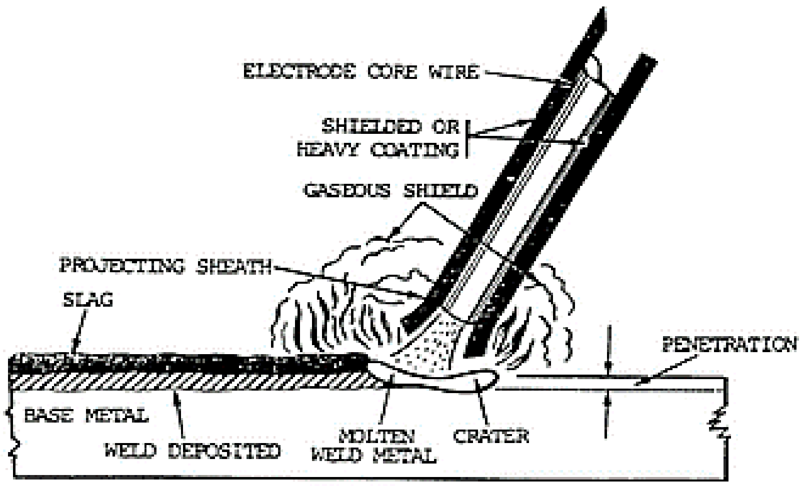


Figure 1.1.a: Shielded Metal Arc Welding (SMAW)

SMAW is one of the oldest and most popular methods of joining metal. Moderate quality welds can be made at low speed with good uniformity. SMAW is used primarily because of its low cost, flexibility, portability and versatility. Both the equipment and electrodes are low in cost and very simple. SMAW is very flexible in terms of the material thicknesses that can be welded (materials from 1/16" thick to several inches thick can be welded with the same machine and different settings). It is a very portable process because all that is required is a portable power supply (i.e. generator). Finally, it is quite versatile because it can weld many different types of metals, including cast iron, steel, nickel & aluminum.

Some of the biggest drawbacks to SMAW are

(1) It produces a lot of smoke & sparks,

(2) There is a lot of post-weld cleanup needed if the welded areas are to look presentable,

(3) It is a fairly slow welding process and

(4) It requires a lot of operator skill to produce consistent quality welds.

1.1.2 Gas Metal Arc Welding (GMAW)

In the GMAW process, (Figure 1.2) an arc is established between a continuous wire electrode (which is always being consumed) and the base metal. Under the correct conditions, the wire is fed at a constant rate to the arc, matching the rate at which the arc melts it.

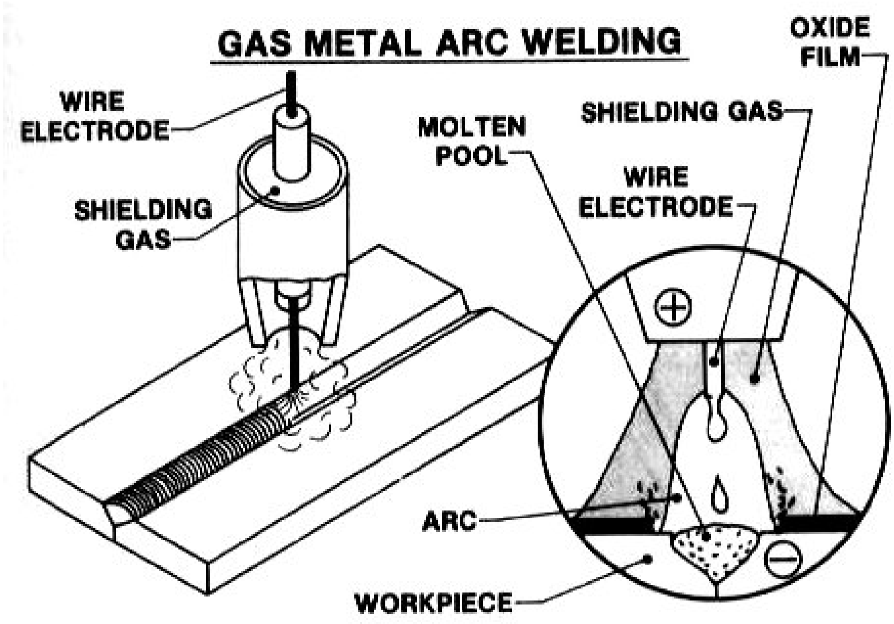


Figure 1.1.b: Gas Metal Arc Welding (GMAW)

The filler metal is the thin wire that is fed automatically into the pool where it melts. Since molten metal is sensitive to oxygen in the air, good shielding with oxygen-free gases is required. This shielding gas provides a stable, inert environment to protect the weld pool as it solidifies. Consequently, GMAW is commonly known as MIG (metal inert gas) welding. Since fluxes are not used (like SMAW), the welds produced are sound, free of contaminants, and as corrosion-resistant as the parent metal. The filler material is usually the same composition (or alloy) as the base metal.

GMAW is extremely fast and economical. This process is easily used for welding on thin-gauge metal as well as on heavy plate. It is most commonly performed on steel (and its alloys), aluminum and magnesium, but can be used with other metals as well. It also requires a lower level of operator skill than the other two methods of electric arc welding discussed in these notes. The high welding rate and reduced post-weld cleanup are making GMAW the fastest growing welding process.

1.1.3 Gas Tungsten Arc Welding (GTAW)

In the GTAW process (Figure 1.3), an arc is established between a tungsten electrode and the base metal(s). Under the correct conditions, the electrode does not melt, although the work does at the point where the arc contacts and produces a weld pool. The filler metal is thin wire that is fed manually into the pool where it melts. Since tungsten is sensitive to oxygen in the air, good shielding with oxygen-free gas is required. The same inert gas provides a stable, inert environment to protect the weld pool as it solidifies. Consequently, GTAW is commonly known as TIG (tungsten inert gas) welding. Because fluxes are not used (like SMAW), the welds produced are sound, free of contaminants and slags, and as corrosion-resistant as the parent metal.

Tungsten is extremely high melting temperature and good electrical conductivity make it the best choice for a non-consumable electrode. The arc temperature is typically around 11,000° F. Typical shielding gasses are Ar, He, N, or a mixture of the two. As with GMAW, the filler material usually is the same composition as the base metal.

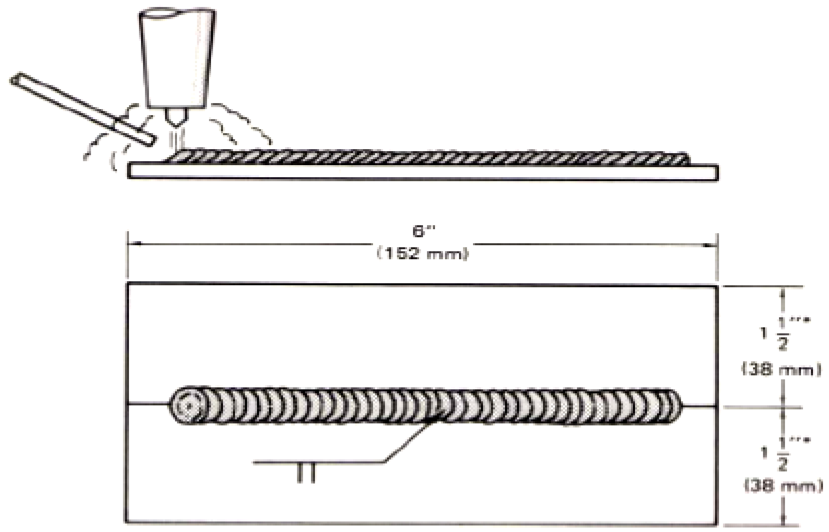


Figure 1.1.c : Gas Tungsten Arc Welding (GTAW)

GTAW is easily performed on a variety of materials, from steel and its alloys to aluminum, magnesium, copper, brass, nickel, titanium, etc. Virtually any metal that is conductive lends itself to being welded using GTAW. Its clean, high-quality welds often require little or no post-weld finishing. This method produces the finest, strongest welds out of all the welding processes. However, it is also one of the slower methods of arc welding.

1.1.4 Selection of the welding process

The selection of the joining process for a particular job depends upon many factors. There is no one specific rule governing the type of welding process to be selected for a certain job. A few of the factors that must be considered when choosing a welding process are:

- Availability of equipment
- Repetitiveness of the operation
- Quality requirements (base metal penetration, consistency, etc.)
- Location of work
- Materials to be joined

- Appearance of the finished product
- Size of the parts to be joined
- Time available for work
- Skill experience of workers
- Cost of materials
- Code or specification requirements

1.2 Background and present state of the problem:

In arc welding, vibration can be applied either during or after the process. When applied after welding, it is generally termed as vibration stress relief, which is a stress relieving method in which controlled vibrations are being applied on welded pieces after welding. Production lead-time can be considerably reduced due to the parallel processing of vibration and welding. Moreover, vibration assisted welding leads to improved microstructure (Prihandana, et al. 2009) and better mechanical properties (Xu, et al. 2009). The different ways in which the vibration is being applied are vibration of work piece during welding, weld pool oscillation, molten droplet oscillation, oscillation of welding arc, vibration of electrode.

There are different modes in which vibration is applied to workpiece such as longitudinal, transverse, vertical and random vibrations. In their oldest available paper, Tewari and Shanker (Jimma, et al. 1998) reported the effect of longitudinal vibration on mechanical properties such as yield strength, ultimate tensile strength and hardness. In their experimental set-up, the workpieces were clamped on a table vibrating longitudinally with the help of an electro dynamic vibrator and welded using manual metal arc welding. Rutile coated mild steel electrodes were used, and the welding current, voltage, energy input, arc length and travel speed of electrode were kept constant. The vibrating conditions, i.e. frequency and amplitude, were in the range of 0–400 Hz and 0–40 μm respectively. Tewari and Shanker (Jimma, et al. 1998) reported that significant enhancement of mechanical properties was observed within the range of 80–400 Hz for frequency and 5–30 µm for amplitude. However, the use of ultrasonic vibrations of frequency of 20 kHz and amplitude of 10–15 µm in vibration assisted gas tungsten arc welding (GTAW) was also reported (Qi, YuanJ. and Xie 2008). Longitudinal vibration of the base metal during arc welding of galvanised carbon steel sheets was reported to be helpful in reducing the number of blowholes formed by vaporised zinc gas bubbles (Mousavi, Feizi and Madoliat 2007). It was observed that there existed an optimum frequency of 30 Hz for these cases at which the number of blow holes was the minimum.

Electromagnetic stirring of molten pool was found to be favouring the grain refinement in gas tungsten arc (GTA) welds of thin sheet made of aluminium alloys (Huang, Lucas and Adams 2002). Stirring of molten metal during CO_2 laser welding with dynamic polarised laser beam resulted in smooth top bead surface (Weber, Herberger and Pilz 1984). Excitation of weld pool using current pulses synchronised with its natural frequency leads to resonance, and thus, the natural frequency may be determined.

The mode of metal transfer has a lot of influence on the quality of welds. Pulsed current gas metal arc welding (GMAW) is a way to achieve controlled metal transfer. An analytical model was developed for explaining the droplet oscillation and detachment process in pulsed current GMAW (Babitsky, et al. n.d.). In pulsed GMAW, the pulse cycle comprises of two periods, droplet growth period and droplet detachment period.

A two dimensional mathematical model was developed to study the effect of electromagnetically oscillated arc on the microstructure and temperature distribution of bead on plate welds on thin tantalum sheets made through GTAW (Skelton 1968).

Electrode vibration has succeeded in improving the metal transfer rate in GMAW. As pointed out by some earlier researchers (Li and Shen 2008) in GMAW, the vibrating electrode cannot simply give sufficient mechanical energy to melt directly additional metal.

In all these processes, mechanical vibrations may have advantageous effect and improve the mechanical properties of the final welded product. Most of the researcher applied longitudinal vibration on GMAW as well as GTAW. However, in conventional arc welding application of horizontal directional vibration and effect of different process parameters have not yet studied.

1.3 Objective with specific aims:

The research work has following objectives:

a) To study the effect of oscillation parameters on welding joints.

b) To develop a model of the oscillation process using statistical approach.

c) To find the optimum working range of values of the oscillation parameters.

1.4 Organization of this thesis

This thesis comprises of five chapters. Chapter 1 gives a brief overview of the background and concept of this study. Finally, significance of the research and the objectives of this study are summarized. This chapter also outlines the organization of this dissertation.

A comprehensive literature review is given in the Chapter 2, which categorized into three sections. First section describes different research work on welding process with oscillation. In the second section, different multi objective optimization processes will be discussed. Finally, extensive literature review on future directions will be discussed.

Chapter 3 describes the methodology and design of experiment of the study. In addition, it describes the optimization algorithm and details description of the algorithm.

Chapter 4 describes the details oscillation assisted welding process. Moreover, the effects of the process parameters are presented in this chapter.

The conclusions and summary of the contributions are presented in chapter 5. In addition, some directions for future work related to this study are also presented.

Chapter 2 Literature Review

2.1 Introduction

Different forms of vibrations such as mechanical vibrations and electromagnetic vibrations imparted to the manufacturing system elements supply extra energy, the proper handling of which leads to improved process performance. For the different types of manufacturing processes, there are broadly two ways in which the vibration is applied, namely, tool vibration (Prihandana, et al. 2009) (Xu, et al. 2009) (Jimma, et al. 1998) (Qi, YuanJ. and Xie 2008) (Mousavi, Feizi and Madoliat 2007) (Huang, Lucas and Adams 2002) (Weber, Herberger and Pilz 1984) (Babitsky, et al. n.d.) (Skelton 1968) and vibration of workpiece. (Li and Shen 2008) (Pilyushenko, et al. 1992) (Nie, et al. 2011) (Abramov, et al. 1995) (W. Wu, Mechanical behavior of the precision component after synchronous vibratory joining 2005) (S. 1999570–574) (Kim, et al. 2008) Some of the specific instances for the first category are vibration of dielectric fluid, (Prihandana, et al. 2009) vibration of tool electrode, (Xu, et al. 2009) vibration of blank holder in deep drawing process, (Jimma, et al. 1998) vibrating wire drawing die, (Qi, YuanJ. and Xie 2008) vibrating extrusion die (Mousavi, Feizi and Madoliat 2007) and vibrating die in upsetting. (Huang, Lucas and Adams 2002) For the second category, there are vibration of flowing melt during extrusion, (Li and Shen 2008) melt vibration (Xu, et al. 2005) and vibrating workpieces during welding. External vibrations in the foregoing processes lead to less cutting (Weber, Herberger and Pilz 1984) (Skelton 1968) or drawing forces (Qi, YuanJ. and Xie 2008) and better surface quality. (Babitsky, et al. n.d.) In casting, the shrinkage defects, blow holes and porosity (Xu, et al. 2005) (Shukla, Goel and Pandey 1980) can be controlled, and the microstructure, (Pilyushenko, et al. 1992) strength of composites (Nie, et al. 2011) and homogeneity (Abramov, et al. 1995) can be improved with the use of vibrations.

In arc welding, vibration can be applied either during or after the process. When applied after welding, it is generally termed as vibration stress relief, which is a stress relieving method in which controlled vibrations are being applied on welded pieces after welding. Continuing the search for higher productivity, researchers are now putting their effort to develop the process of arc welding during vibration, i.e. vibration assisted welding (VAW), which can cut most of the expenses related to post weld vibrations or heat treatments. Production lead time can be considerably reduced due to the parallel processing of vibration and welding. Moreover, VAW leads to improved microstructure (W. Wu, Mechanical behavior of the precision component after synchronous vibratory joining 2005) and better mechanical properties. (S. 1999570–574) The different ways in which the vibration is being applied are listed below:

(i) Oscillation of workpiece during welding,

(ii) Weld pool oscillation,

(iii) Molten droplet oscillation,

(iv) Oscillation of welding arc,

(v) Oscillation of electrode.

Different modes of vibration are associated with any one of the constituents of welding system that includes workpiece, electrode, welding arc, weld pool and power source. The first four constituents can be physically agitated, whereas the power source can provide vibration to the molten droplet by supplying pulsed current as shown in Figure 2.1. All the above mentioned types of vibrations can be classified into two groups: vibration of workpiece in a welding system and vibration of various elements other than the workpiece in a welding system. The first group consists of vibration of workpiece and vibration of weld pool. Vibration of workpiece and oscillation of weld pool are closely related to each other, because the former leads to the latter. However, direct agitation of weld pool is also possible through pulsating gas shielding described later.

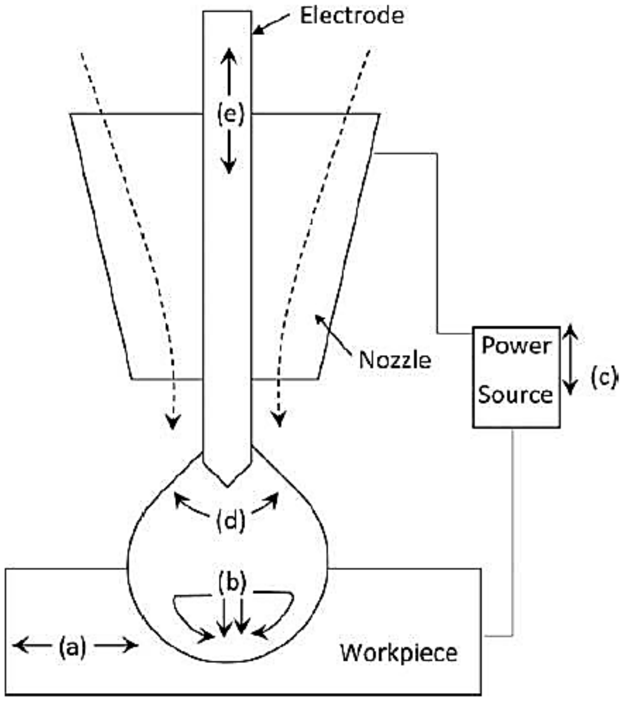


Figure 2.1.a: Modes of vibration assisted welding

In the figure 2.1 (a) vibration of workpiece; (S. 1999570–574) (Kim, et al. 2008) (Tewari and Shanker, Effects of longitudinal vibration on the mechanical properties of mild steel weldments 1993) (Methong and Poopat 2013) (Chen and Hsu 1998) (Tewari and Shanker, Effects of longitudinal vibration on tensile properties of weldments 1994) (P and Anand 1993) (S. 1999570–574) (Matsui and Shionoya, Reduction of blowholes by vibration of the molten pool in arc welding of galvanised carbon steel sheet 1998) (W 1999) (Munsi, Waddell and Walke, The effect of vibratory stress on the welding microstructure and residual stress distribution 2001) (Munsi, Waddell and Walker, Modifcation of welding stresses by flexural vibration during welding 2001) (Pucko and Gliha, Effect of vibration on weld metal hardness and toughness 2005) (Zhu, Chen and Rao 2005) (Pucko, Charpy toughness of vibrated microstructures 2005) (Aoki, Nishimura and Hiroi, Reduction method for residual stress of welded joint using random vibration 2005) (Cui, Xu and Han, Effect of ultrasonic vibration on unmixed zone formation 2006) (Pucko and Gliha, Charpy toughness and microstructure of vibrated weld metal 2006) (Aoki, Nishimura, et al., Reduction of residual stress of welded joint using local plasticity caused by ultrasonic vibration 2007) (Xu, Chen and Ni, Effects of vibratory weld conditioning on residual stresses and transverse contraction distortions in multipass welding 2006) (Xu, Chen and Ni 2007) (Lu, Chen and Ni, Improving welded valve quality by vibratory weld conditioning 2007) (Lu, Chen and Ni, Effect of vibratory weld conditioning on welded valve properties 2008) (Pucko, Effect of vibratory weld conditioning on weld impact toughness 2009) (Balasubramanian, Kesavan and Balusamy 2011) (Dehmolaei, Shamanian and Kermanpur 2008) (Tewari and Shanker, Effects of longitudinal vibration on tensile properties of weldments 1994) (Lee, et al. 2007) (Dong, et al. 2012) (Cui, Xu and Han, Microstructure improvement in weld metal using ultrasonic vibrations 2007) (Chen and Zhang 2015) (Xu, et al. 2014) (Liu, Wu and Padhy 2015) (Gao, et al. 2014) (Ye, et al. 2015) (b) weld pool oscillation; (Matsuda, et al. 1978) (Graf, et al. 2010) (Matsui, Chiba and Yamazaki, Detection and amplification of the molten pool natural oscillation in consumable electrode arc welding 2014) (Sorensen and Eagar, Modeling of oscillations in partially penetrated weld pools 1990) (Andersen, et al. 1997) (Sorensen and Eagar, Measurement of oscillations in partially penetrated weld pools through spectral analysis 1990) (Aendenroomer and Den Ouden n.d.) (Yamamoto, et al. 1993) (Renwick and Richardson 1983) (Xiao and Den Ouden 1990) (Wang and Hong 2010) (Kishore Babu and Cross 2012) (Xiao and den Ouden 1993) (Liu, Tang and Lu 2013) (Krajewski, et al. 2012) (Ju, Suga and Ogawa May 2002) (Singh, Kumar and Garg 2012) (Watanabe, et al. 2010) (c) molten droplet oscillation using pulsed current; (Wu, Chen and Li 2004) (Chen, et al. 2006) (Yudodibroto, et al. 2006) (Hirata, et al. 2007) (d) oscillation of welding arc; (Grill 1981) (Kou and Le 1985) (Starling, et al. 1995) (Sundaresan and Ram 1999) (Zhang, et al. 2009) (Rao, et al. 2005) (Kuo, et al. 2008) (Lim, et al. 2010) (Zhang and Zou 2010) (Biradar and Raman, Investigation of hot cracking behavior in transverse mechanically arc oscillated autogenous AA2014 T6 TIG welds 2014) (Biradar and Raman, Grain refinement in Al–Mg–Si alloy TIG welds using transverse mechanical arc oscillation 2012) (Mahajan, et al. 2012) (Wang, et al. n.d.) (e) vibration of electrode (Jones, Eagar and Lang june 1992) (Sun, et al. 2008) (Fan, et al. 2010) (Fan, et al. n.d.)

With the evolution of the microstructure of welds being an important factor in stress reduction and distortion, VAW may prove more beneficial compared to vibration stress relief as post-weld vibrations have no role in shaping the microstructure of welds. Vibration assisted welding actively influences the process of solidification of weld metal, which determines its mechanical properties. With the improvement in mechanical properties and reduction in production lead time, residual stress and distortion, associated with VAW, being unambiguously established, the need of the hour is to extend its scope to hotter areas like possible savings in heat input and effects on element transfer. Selection of suitable vibration parameters for VAW provides ample scope for engineers to produce the welds of their choice and demand. Design of a competent VAW system necessitates deep knowledge and expertise not only in welding engineering but also in the areas of vibration engineering, metallurgy and design engineering. The interdisciplinary nature of VAW demonstrates the seemingly available immense potential for its growth. The beginning of such a leap needs a platform, consolidated with the summary of findings, merits, demerits and shortfalls identified hitherto in the field of VAW, which is exactly the purpose of this review paper. The techniques and processes of imparting externally controlled vibrations to the different elements of the welding system along with their effects on microstructure, mechanical properties and residual stresses related to welded joints are reviewed extensively. Some of the analytical and mathematical models relevant to the context are also discussed. The following sections pre-sent the state-of-the-art survey on the foregoing techniques followed by a discussion on the future direction in the area of VAW.

2.2 Vibration of workpiece during welding

There are different modes in which vibration is applied to workpiece such as longitudinal, transverse, vertical and random vibrations. In their oldest available paper, Tewari and Shanker (Tewari and

Shanker, Effects of longitudinal vibration on the mechanical properties of mild steel weldments 1993) reported the effect of longitudinal vibration on mechanical properties such as yield strength, ultimate tensile strength and hardness. Schematic diagram for experimental set-up is shown in Figure 2.2. Workpieces were clamped on a table vibrating longitudinally with the help of an electro dynamic vibrator and welded using manual metal arc welding.

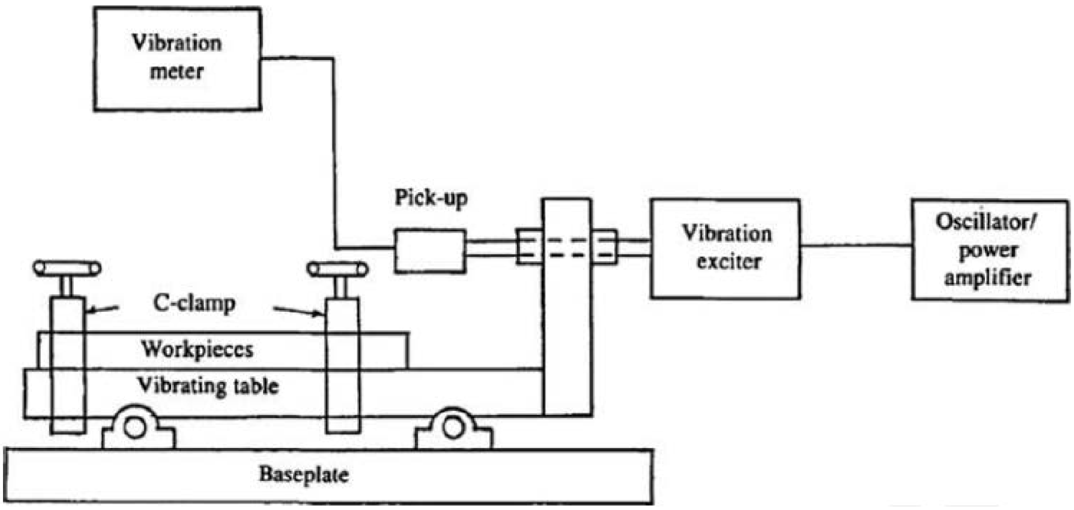


Figure 2.2.a : Schematic diagram for experimental set-up (Tewari and Shanker, Effects of longitudinal vibration on the mechanical properties of mild steel weldments 1993)

Rutile coated mild steel electrodes were used, and the welding current, voltage, energy input, arc length and travel speed of electrode were kept constant. The vibrating conditions, i.e. frequency and amplitude, were in the range of 0–400 Hz and 0–40 mm respectively. In general, low frequency and low amplitude vibrations are given to workpieces during welding by considering the mass of the system to be vibrated. However, the use of ultrasonic vibrations of frequency of 20 kHz and amplitude of 10–15 mm in vibration assisted gas tungsten arc welding (GTAW) was also reported. (Methong and Poopat 2013) The maximum output power of vibration was 1.4 kW. The filler metal ER70S-G was melted into water cooled copper mould, which was vibrated ultrasonically with the help of a horn. In addition to the manual metal arc welding and GTAW, other welding and allied processes like gas metal arc welding (GMAW), submerged arc welding (SAW), flux cored arc welding (FCAW) and electrogas welding (EGW)16 and Nd:YAG pulsed laser ceramic–metal composite cladding (Chen and Hsu 1998) were also reported as working with vibrating workpieces. The vibration of workpiece leads to various qualitative changes in the welds. The majority of those re given as follows.

2.2.1 Effect on mechanical properties

Tewari and Shanker (Tewari and Shanker, Effects of longitudinal vibration on the mechanical properties of mild steel weldments 1993) reported that significant enhancement of mechanical properties was observed within the range of 80–400 Hz for frequency and 5–30 mm for amplitude. In another investigation, breaking strength, ultimate tensile strength (UTS) and yield strength of specimen made under longitudinal vibratory conditions registered an improvement of (Ju, Suga and Ogawa May 2002) (Munsi, Waddell and Walker, Vibratory weld conditioning — the effect of rigid body motion vibration during welding 1999) and 2%respectively. (Tewari, Influence of longitudinal oscillation on tensile properties of medium carbon steel welds of different thickness 2009) However, the effect of specimen thickness on tensile properties was insignificant. The reason for the improvement in mechanical properties is grain refinement due to vibration. The grain refinement also leads to reduction in elongation by 5.5%. Under the identical conditions of vibration, the hardness improved both at the center and at the extreme ends of weldments, and this increase was, by and large, uniform in contrast to what was observed in stationary welding. (P and Anand 1993) Vibration during welding produces finer grains and uniform distribution of grains that results in improvement in hardness. The energy absorbed by the welds during Izod test is found to be higher for those prepared under vibratory conditions compared to those made normally. (S 1999) Ultimate tensile strength, yield strength and breaking strength of weld made under conditions of transverse oscillations were higher, and the improvement was apparent within the ranges of 80–400 Hz for frequency and 5–30 mm for amplitude. The ductility was diminished, and finer grains were formed. (S. 1999570–574)

Longitudinal vibration of the base metal during arc welding of galvanized carbon steel sheets was reported to be helpful in reducing the number of blow holes formed by vaporized zinc gas bubbles. (Matsui and Shionoya, Reduction of blowholes by vibration of the molten pool in arc welding of galvanised carbon steel sheet 1998) In the vibratory set-up, the base metal was fixed to a jig, which oscillated to and fro through a connecting rod due to rotation of an eccentric cam. The movement of welding torch was independent of vibration. Back and forth, flow of hot metal within the weld pool due to vibrations resulted in less number of blow holes. Further investigation suggested that the longitudinal vibration of weld pool could also be realized by pulsed current wave form groups such as of high peak/short time and low peak/long time. It was observed that there existed an optimum frequency of 30 Hz for the above two cases at which the number of blow holes was the minimum. The removal of super saturation blow holes developed due to nitrogen was also assisted by the vibration.

Vibration during the process helped to reduce the shrinkage cavity defect for smaller depth of penetration in high power Nd:YAG pulsed laser ceramic–metal composite cladding on aluminium alloy A6061.21 Vibration waves of different forms like rectangular, sinusoidal and burst were generated at frequencies 50, 100, 200, 500, 1000, 1500 and 2000 Hz. Acceleration sensing device monitored the frequency and amplitude of vibration helping to control the amplitude of specimen vibration more accurately. The sine wave modulation turned out to be more significant in improving the shrinkage cavity.

When the specimens were vibrated in rigid body motion mode during welding, the process was ineffective in reducing both the longitudinal and transverse residual stresses. (Munsi, Waddell and Walker, Vibratory weld conditioning — the effect of rigid body motion vibration during welding 1999) Single pass bead weld was performed on flat bar using metal inert gas (MIG) welding set up at frequencies of 50 and 500 Hz. During semiautomated GTAW of nickel alloy 690 to form single V butt joint, (W 1999) (W. Wu, Influence of vibration frequency on solidifcation of weldments 2000) the workpieces were vibrated by a rotating cam through a vibrating table, and the experiments were conducted at three chosen frequencies of 0 and 48 Hz (sub resonant vibration) and 58 Hz (resonant vibration). The hardness of weldments made with vibration was found to be less than that without vibration. Vibration affected the process of solidification breaking up the dendrites without allowing them to grow larger and thus produced finer grains. Diminished residual stress, lower tensile strength and elongation and less hardness were also reported. Finer microstructures and lower residual stresses were observed with the vibration assisted semi-automated multipass GTAW of Inconel alloy 690.14 Sub resonant frequencies and resonant frequency were chosen for the experiment in addition to a welding condition of without vibration. Sub resonant vibration resulted in more randomized grain orientation, and reduction in residual stresses was higher compared to those developed with resonant vibration and without vibration. Tensile strength, ductility and hardness of weld metal were found diminished because of the externally applied mechanical vibration during welding.

When vibration was applied to cold rolled mild steel specimens during MIG welding, it resulted in grain refinement, reduction in residual stress and increase in hardness. (Munsi, Waddell and Walke, The effect of vibratory stress on the welding microstructure and residual stress distribution 2001) The frequency of vibration was maintained at 25 Hz during vibratory welding. Heat input, welding speed and time of vibration were also kept constant, and amplitude was varied. During post-weld vibratory treatment, the applied stress was kept constant, and time of vibration was kept varying. Residual stress was diminished in both the cases. Post-weld vibratory treatment was reported as not having any significant impact on the microstructure of welded zone. The high amplitude vibrations produced a joint of higher hardness and more refined grains.

Flexural vibration as applied to specimens made of 0.18 wt-%C steel during the single pass MIG bead on plate welding led to fall in both transverse and longitudinal residual stresses. (Munsi, Waddell and Walker, Modifcation of welding stresses by flexural vibration during welding 2001) The flexural vibrations at a non-resonant frequency of 25 Hz were applied to the specimen. The effect of amplitude of vibration on the development of residual stresses was studied keeping frequency constant, and the residual stress was found as a function of amplitude and thus that of applied stress. Level of amplitude of vibration was kept constant to study the effect of time of vibration, and it was proved insignificant. Application of a frequency as high as 341.5 Hz did not result in a reduction in residual stress, as expected due to increase in energy input. Optimum amplitude of vibration was observed at which the decline in both transverse and longitudinal residual stresses was the maximum.

The effect of vibration of specimen during welding on hardness and toughness of weld metal was studied in the case of two welding processes, namely, SAW and transferred ionized molten energy (TIME). (Pucko and Gliha, Effect of vibration on weld metal hardness and toughness 2005) Transferred ionized molten energy is a high performance process variant of MIG/metal active gas welding. The TIME process is the most economical one for very long weld seams with large cross-section and high metal de-position rate. This process has greater 'stick-out', faster wire speed and modified shielding gases. Niomol490K was the base material used to make K butt joint, and the frequency of vibration was a sub resonant one. The hardness distributions for the two processes were different owing to different welding parameters and filler materials. Average value of hardness for vibration assisted SAW was less than that without vibration. Both the impact toughness and fracture toughness in multi-pass welding got enhanced with vibration, and the latter was increased up to 80%. There was not any substantial change in microstructure for multipass weld made with vibration. It was found that, in comparison with TIME, the change in microstructure was more evident in SAW. Figure 2.3 shows the difference between structures of normal and vibrated weldments in SAW. The former is more dendritic and oriented than the latter.

Vibration assisted welding has been proved to be beneficial for electro slag welding also. (Zhu, Chen and Rao 2005) The weld was made under two different types of vibratory conditions, namely, 0.3 and

0.6 g acceleration. Residual stresses were diminished largely with the maximum stress being less than half of the yield strength. Vibration assisted welding helped to produce finer grains, and grain size in the case of 0.6 g acceleration was smaller than that of the other. Again, continuing the vibration even after welding resulted in further relieving of residual stress. When the specimens made of Niomol490K were welded using SAW method under the condition of specimen vibrating, the toughness was found improved. (Pucko, Charpy toughness of vibrated microstructures 2005) In addition to single pass welding, the effect of multipass welding was also simulated, and toughness increased in all the cases. Even though the difference between toughness values of vibrated and normal welds was small in the case of single pass welding, it was apparent in multipass welding. It was concluded that such microstructures favorable to high toughness might have been formed during the process of vibration that further heating could not affect them much. (Pucko, Charpy toughness of vibrated microstructures 2005) The vibration during welding also promoted ductile fracture of welds.

Reduction in residual stress was also observed when random vibration was applied to the workpieces during welding using an automatic acid carbon gas shielded welding machine. (Aoki, Nishimura and Hiroi, Reduction method for residual stress of welded joint using random vibration 2005) Random vibration comprised of wide range of frequencies and white noise, and filtered white noise were chosen as representatives for the process. Thin plates of rolled steel were butt welded along X shaped groove, and tensile residual stresses were found to be diminished by 22 and 14% on first and second welded sides respectively. Figure 2.4 shows the distribution of residual stress both along the longitudinal direction and over the bead.

The ultrasonic vibrations applied to the workpieces during the bead on plate shielded metal arc welding (SMAW) of AL-6XN super austenitic stainless steel could completely eliminate the formation of unmixed zone. (Cui, Xu and Han, Effect of ultrasonic vibration on unmixed zone formation 2006) Unmixed zone is a boundary layer beside the fusion boundary and consists of base metal that melts and solidifies during welding without undergoing mechanical mixing with filler metal. (Cui, Xu and Han, Effect of ultrasonic vibration on unmixed zone formation 2006) Ultrasonic vibrations at frequency of 20 kHz were applied on the specimen in a direction perpendicular to it using ultra-sonic generator and ultrasonic radiator. The proposed process was claimed to be capable of increasing the corrosion resistance of the weldment. Charpy toughness and microstructure of weld metal in vibration assisted SAW were further studied, and it was found that vibration during multipass welding helped to improve the weld metal toughness, while vibration during single pass welding did not have any significant effect on tough-ness. (Pucko and Gliha, Charpy toughness and microstructure of vibrated weld metal 2006) The single pass welds were made on high strength low alloy steel with vibration and without vibration, and there was difference in microstructure of the two.

The effect of imparting ultrasonic vibrations of different frequencies to the two thin plates made of rolled steel during butt welding by acid carbon gas sealed arc welding machine was studied by some researchers. (Aoki, Nishimura, et al., Reduction of residual stress of welded joint using local plasticity caused by ultrasonic vibration 2007)

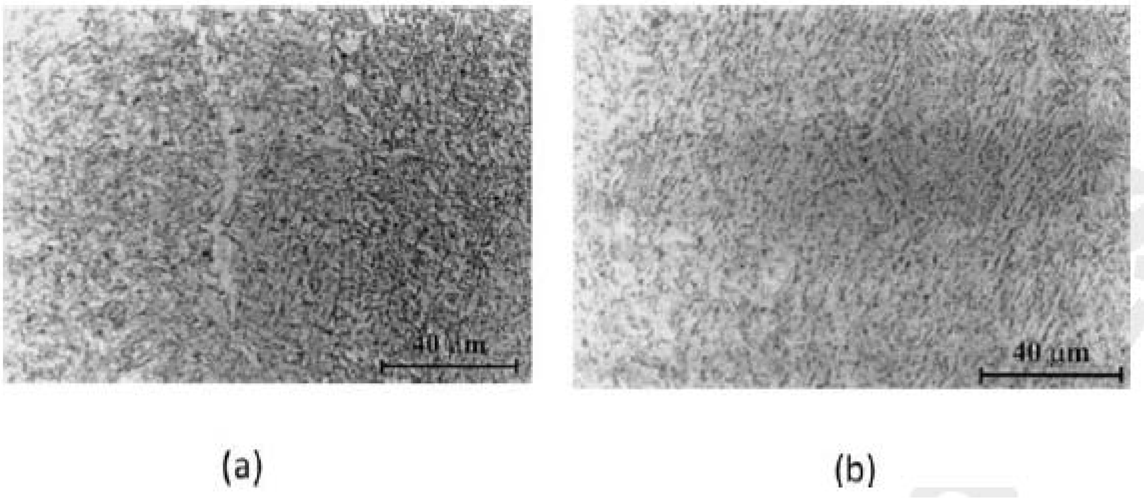


Figure 2.2.b : Microstructure of weld by SAW a without vibration and b with vibration (Pucko and Gliha, Effect of vibration on weld metal hardness and toughness 2005)

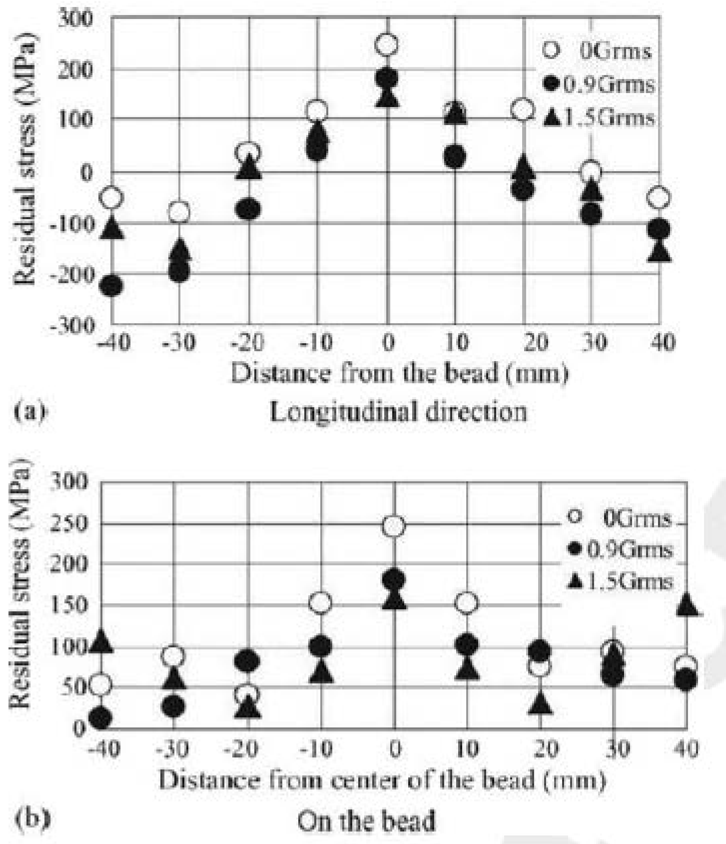


Figure 2.2.c : Residual stress distribution (a longitudinal direction; b on bead (Aoki, Nishimura and Hiroi, Reduction method for residual stress of welded joint using random vibration 2005)

In the first part of their experiment, Ultrasonic vibration at frequency of 60 kHz was applied on one plate, and tensile residual stress at the center of bead got reduced. In the second part, ultrasonic vibrations at frequencies of 60 and 27.5 kHz were applied to the two thin plates leading to higher rate of reduction in residual stress. Further, with the help of a two-dimensional spring mass model, the reduction in tensile residual stress in and around the bead was demonstrated. The concept behind the proposed model was that the low yield strength of material at the weld zone immediately after welding facilitated relieving of residual stresses through plastic deformation by absorbing energy from ultrasonic vibrations.

Introducing VAW into the multipass single wire SAW of full welded valves, both residual stresses and trans-verse contraction distortion were lessened largely, and finer grains were formed for weld metal.38 A105 forged steel being the base material, the workpieces were vibrated during welding. The vibratory set-up comprised of a rotating eccentric wheel that produced oscillations, an acceleration sensor that measured vibratory accelerations, a controller to control the accelerations and a test platform supported by rubber pads. The maximum residual stress was brought down with VAW to a point lower than yield strength, making the distribution of residual stress more uniform and the welded joint safe. Experimental study of multipass girth butt welded pipes, made through the process of single wire SAW and assisted by VAW, showed that the process had profound effect on residual stresses and distortion. (Xu, Chen and Ni 2007) The forged steel A105 was used as base material. The workpieces were vibrated during welding with the help of the rotation of an eccentric wheel and a platform supported by rubber pads. The VAW process succeeded in reducing the residual hoop stresses at the outer surface and its maximum value. Residual axial stresses at the outer surface were only slightly affected. With VAW, the residual stresses were found to be less than the yield stress. While the process reduced the radial distortion by 50%, it could not do much in the case of axial distortion. The VAW was applied to investigate its effect on the properties of valves welded through SAW, and there was no significant change in yield strength and tensile strength. (Lu, Chen and Ni, Improving welded valve quality by vibratory weld conditioning 2007) (Lu, Chen and Ni, Effect of vibratory weld conditioning on welded valve properties 2008) The workpiece material was forged steel, A105. Two cylinders of equal outer diameter and different inner diameters were butt welded in multipass SAW with a vibrating platform on which the workpieces were clamped. The bending property was found to be increased with vibration. Grain refinement, enhanced removal of gas and hence reduced porosity, significant reduction in welding deformation and residual stress and uniform welded joint were cited as other advantages of applying VAW. The Charpy impact toughness was increased by 21% for weld metal and decreased by 0.9%for heat affected zone (HAZ). The energy due to vibration helped to break up the growing dendrites, thus producing finer grains.

Effect of vibrating the specimen during FCAW and EGW of AH-32 and DH-32 steels respectively on residual stress and microstructure was studied. (Kim, et al. 2008) Flux cored arc welding was performed as multipass welding for which weld metal formed with vibration was found as having higher toughness, and its microstructure was finer and isotropic without any columnar structure. The stirring effect created by vibration on the weld pool made the rate of cooling larger preventing the formation of large dendrite structures. In single pass EGW, appreciable difference was there between microstructures of vibrated and normal welds. At the same time, multipass welding with vibration produced hardly any change in microstructure.

Vibration assisted welding was found to be adding to Charpy toughness of the weld metal in an experimental study (Pucko, Effect of vibratory weld conditioning on weld impact toughness 2009) in which four single welded plates of base material Niomol490K were made with SAW process under four different conditions, namely, as welded, heat treated to 500uC after welding for 20 min, vibratory weld conditioned and combination of above two with vibration during heating, and the weldments were subjected to impact testing. The vibration enhanced the impact energy of single welded plates, tempered single pass welds exhibited less toughness and multipass welds acquired higher toughness.

Vibration assisted welding was proposed as a process capable of replacing post-weld heat treatment in reducing the welding residual stresses in fully welded body ball valve. (Xu, Chen and Ni, Low stress welding technology without post-weld heat treatment 2009) Workpieces made of forged steel A105 were vibrated during welding, and residual stresses were measured using blind hole drilling method. Vibration during welding could reduce the residual hoop stress at the outer surface, and residual axial stress hardly changed at the outer surface. It was observed from experiments that the residual stresses were lower than yield stress, thereby ensuring the safety of welded valve. The crack tip opening displacement values for HAZ and weld metal with vibration during welding were found more than that without vibration. These crack tip opening displacement values were larger than the critical value by which it was confirmed that there was no need of further post-weld heat treatment.

During GTAW of aluminum alloy AA7075, it was found that the process led to reduction in hot cracking and finer grain size in comparison with those weldments produced without vibration. (Balasubramanian, Kesavan and Balusamy 2011) Vibrations of frequency within the range of 100–2050 Hz were generated using a piezoelectric transducer and applied to the workpieces during welding. Houldcroft test was conducted to assess the resistance to hot cracking, and the hardness of the weld metal was found increasing with the frequency of vibration.

The mechanical properties of the weld such as ductility and tensile strength along with homogeneity were found to be enhanced with the help of VAW. (Hussein, Jail and Abu Talib 2001) The process of manual arc welding was performed on hot rolled mild steel plates with the assistance of harmonic vibration at frequencies of 3, 5, 10 and 100 Hz during the welding, and the subsequent bending and tensile tests disclosed that both the ductility and tensile strength were increased. While the pieces made through VAW developed no cracks, those made without vibration did it. It was claimed that the vibration energy provided helped to have better homogeneity in welded zone.

High frequency electromagnetic vibrations imparted to the workpieces during GTAW of two dissimilar materials 25Cr–35Ni heat resistant steel (HP steel) and alloy 800 super alloy could successfully eliminate the unmixed zone. (Dehmolaei, Shamanian and Kermanpur 2008) Copper coil, located under the work table, produced the alternating magnetic field for the electromagnetic vibration. The experiment was con-ducted at four different potentials, namely, 0 (without vibration), 3, 12 and 24 V. The vibration resulted in stirring of weld pool causing complete mixing of filler material, alloy 82, with base materials and eliminated unmixed zone. The level of mixing was higher with higher value of potentials. Vibration affected the solidification behavior of molten pool. Longitudinal vibration of 8 mm MS workpieces during welding led to improvement in yield strength, UTS and breaking strength but caused reduction in percentage of elongation. (Tewari and Shanker, Effects of longitudinal vibration on tensile properties of weldments 1994) The range of frequency was 0–400 Hz, and 0–40 mm was the range for amplitude. The tensile properties increased with increase in frequency, but they decreased generally with increase in amplitude.

The fatigue strength of weldment made of SM 490A steel of weldable grade was improved only slightly with mechanical vibrations of workpieces during FCAW. (Lee, et al. 2007) The experimental set-up had a mechanical vibration apparatus consisting of rotary vibrator, programmable logic controller, sensor and analyser. The experiment was conducted at the resonant frequency of 60 Hz. The vibration resulted in grain refinement, and a different microstructure and mechanical properties of specimen such as tensile strength, impact strength and hardness were improved.

Microstructure improvement through grain refinement was reported in ultrasonic vibration assisted SMAW of 304 stainless steel plates of 12 mm thick-ness. (Cui, Xu and Han, Microstructure improvement in weld metal using ultrasonic vibrations 2007) The experimental set-up included ultrasonic generator, waveguide and welding equipment. The direction of ultrasonic vibration was normal to that of the plane of specimen. The vibration changed the microstructure of weld metal from columnar dendritic to fine equiaxed dendritic microstructure.

Aluminum was joined to galvanized steel with aluminums at the top and steel at the bottom through ultrasonic vibration assisted GTAW. (Dong, et al. 2012) Ultrasonic probe of 28 mm diameter rested vertically over the aluminum sheet at a distance of 30 mm from weld pool and vibrated axially at a frequency of 20 kHz. The weight of probe and vibration holder acted on workpiece down-wards. Figure 2.5 shows the schematic diagram for the process. Grain refinement of weld metal and increase in micro-hardness for both HAZ and weld metal were reported as the result of this process. An increase of 27%in tensile strength could be achieved with the ultrasonic vibration assisted GTAW process. The acoustic cavitation happening in weld pool due to the ultrasonic vibrations was stated to be the reason for greater nucleation and dendrite fragmentation which results in grain refinement.

Heat generation and temperature distribution in ultrasonic welding with Cu and Al were studied by Chen and Zhang (Chen and Zhang 2015) using a three-dimensional finite element model. The model was composed of workpieces, sonotrode and backing anvil. Uniformly distributed force was applied normally on the Cu and Al plates through sonotrode, and the sonotrode vibrated laterally over the plates. Frequency of ultrasonic vibration, applied force and amplitude of sonotrode vibration were considered as the welding process parameters. It was observed that the heat generated due to plastic deformation was nearly a quarter of the total heat generated, which was the sum of heat generated due to plastic deformation and inter-face friction. Because of the huge amount of frictional heat generation, the maximum temperature was found to be located at the contact surface of specimens.

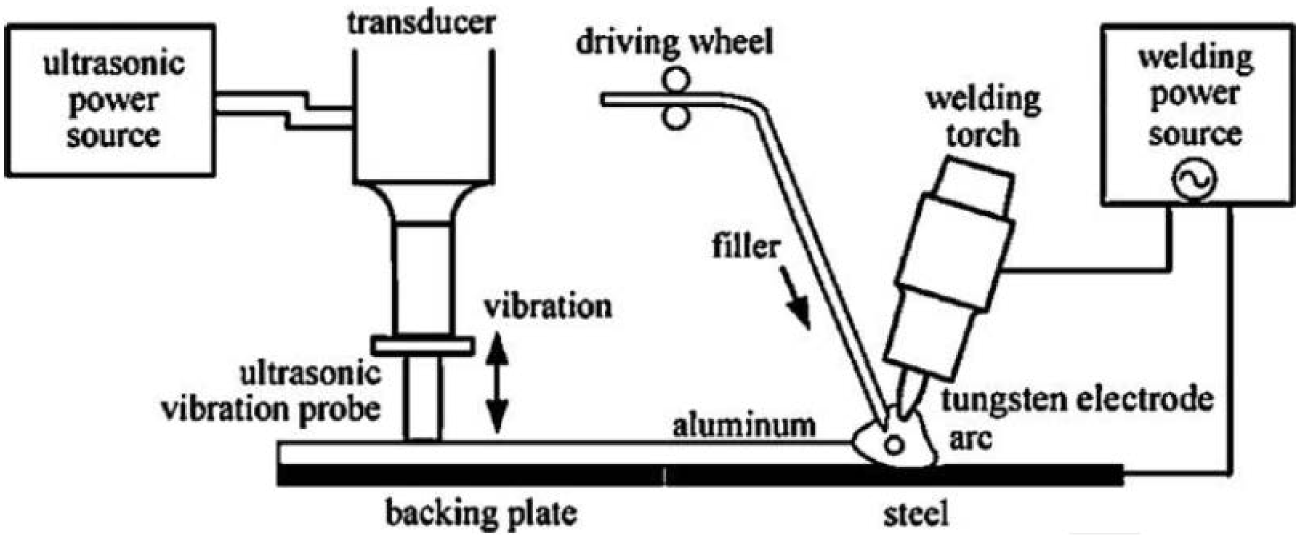


Figure 2.2.d : Schematic diagram for ultrasonic vibration assisted GTAW process (Dong, et al. 2012)

Grain refinement in fusion zone was reported by Xu et al. (Xu, et al. 2014) based on their experimental study on ultrasonic vibration assisted tungsten inert gas (TIG) welding for making Mg/Ti joints. The ultrasonic vibration system was of 1.6 kW maximum output power, 30 mm output amplitude and 20 kHz output frequency. The direction of vibration was normal to the workpiece. The average size of a-Mg grains was reduced to one-fourth. In comparison with joints made without ultrasonic vibration, the joint strength was increased by 18.1%.

The softening effect of ultrasonic vibration helped to achieve good weld formation and mechanical properties in friction stir welding. (Liu, Wu and Padhy 2015) The base metal used was of 3 mm thick commercial 2024Al-T4 rolled plates, and butt-welding was performed with and without localised ultrasonic vibration. Schematic of the process is given in Figure 2.6. The vibration tool head that was connected to an ultrasonic amplitude transformer transmitted vibration into material around the too pin at a distance of 20 mm ahead the tool. Ultrasonic vibration system worked with a frequency of 20 kHz, output power of 300 W and amplitude of 40 mm. It was reported that the but welding speed could be increased with such vibrations. Micro hardness of the weld nugget zone and tensile strength of joints were improved.

A comparative study between ultrasound and ultra-sonic impact treatments (UITs) was conducted in multipass GMAW with 16 mm thick steel plates. (Gao, et al. 2014) The ultrasonic transducer was applied to the weld toe with and without mechanical impacts as post-weld treatments. The vibration amplitude of transducer was 28 mm, and the operating frequency of transducer was 27 kHz. Residual stresses were measured along two orthogonal directions.

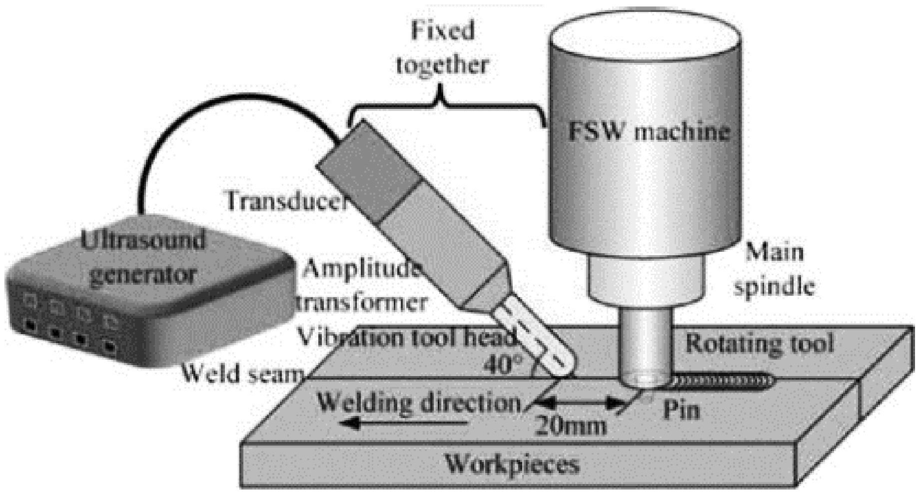


Figure 2.2.e : Schematic of ultrasonic vibration assisted friction stir welding (Liu, Wu and Padhy 2015)

It was found that the UIT was effective both in releasing and redistributing residual stresses. Application of only ultrasonic transducer at the weld toe was more effective than UIT in redistributing the residual stresses uniformly. The combination of ultrasound with mechanical impacts was reported to be an effective method to release residual stresses. Another post-weld treatment to reduce residual stresses and improve the surface mechanical properties was reported by Ye et al., (Ye, et al. 2015) and this process is called electropulsing assisted ultrasonic impact treatment. The base material was 12 mm thick medium carbon steel plates, and metal active gas welding was performed at a speed of 3.8 mm s21. Ultrasonic impact treatment was applied at the weld surface, and simultaneously, electro pulsing was applied at both ends of welded components. Electro-pulsing assisted ultrasonic impact treatment appeared to be better in eliminating welding residual stresses than conventional UIT. Electro pulsing assisted ultrasonic impact treatment helped to improve micro hardness and modify surface microstructure. Electro plasticity due to electro pulse current was said to be reducing the deformation resistance and improving the ultrasonic strike efficiency.

2.3 Weld pool oscillation

Electromagnetic stirring of molten pool was found to be favoring the grain refinement in gas tungsten arc (GTA) welds of thin sheet made of aluminum alloys. (Matsuda, et al. 1978) The electromagnetic stirring apparatus had a magnetic coil with a ferrous core at the canter. The coil was fixed under the specimen and in line with the axis of welding torch. The stirring effect was produced in molten pool as the result of interaction of alternating magnetic field with arc current. Existence of optimum frequency for alternating magnetic field was observed for grain refinement, and this frequency was proportional to the welding speed. Formation of porosities was reduced due to stirring, and an optimum condition of frequency and intensity of magnetic field existed for this. The stirring helped to eliminate formation of feathery crystal and homogenies the composition of weld metal. Stirring of molten metal during CO2 laser welding with dynamic polarized laser beam resulted in smooth top bead surface. (Graf, et al. 2010) The workpiece was made of steel St37 with nickel foils placed between steel sheets as contrast material. The contrast material helped for appropriate visualization of molten pool stirring. Stirring at 250 Hz led to the lowest top bead roughness. The characteristics of weld-like penetration can be controlled with the knowledge of natural frequency of vibration of weld pool, as the frequency is directly linked to the properties of the weld pool and its size and shape. The size and shape of weld pool are decided by the heat input, thickness of base metal and type of base metal. The oscillating force and shape of weld pool determine the modes of oscillation. The natural frequency of weld pool decreases with increase in size, and it can be detected with the help of resonance phenomenon due to the oscillation imparted to base plate. (Matsui, Chiba and Yamazaki, Detection and amplification of the molten pool natural oscillation in consumable electrode arc welding 2014) The natural oscillation was successfully amplified using modulated pulse.

Two theoretical models, one a lumped parameter model and another a distributed parameter model, were proposed for natural frequency of oscillations of partially penetrated weld pools in the case of stationary GTAW. (Sorensen and Eagar, Modeling of oscillations in partially penetrated weld pools 1990) The models help to predict weld pool geometry from the knowledge of natural frequency of oscillations, which can be measured by monitoring arc voltage and current. The natural frequency of the weld pool from the lumped parameter model is

$$\omega^{n} = \frac{g}{D}\frac{1}{b^2(1-b^2)} + \frac{12\gamma}{\pi\rho D W^2}\frac{[b^4+2\,(1-b^2)^2]}{b^4\,(1-b^2)^2} \tag{2.1}$$

where ω_n is the resonant cyclic frequency of weld pool oscillations, each portion of weld pool acts as an inductance element whose length is D, g is the acceleration due to gravity, γ is the surface tension of liquid metal W= is the width of weld pool, b is the ratio of diameter of inner tank to total weld pool width (W1/W2) and ρ= is the liquid density.

As per the distributed parameter model, natural frequency of the infinite depth weld pool is

$$\omega_n^2 = \frac{7.66g}{W} + \frac{449\gamma}{W^3\rho} \tag{2.2}$$

Natural frequency of the finite depth weld pool is

$$\omega_n^2 = \left(\frac{7.66g}{W} + \frac{449\gamma}{W^3\rho}\right)\tan h(7.66/W) \tag{2.3}$$

In the case of zero surface tension, the models from the two different approaches match completely. It was learned from all these models that frequency of weld pool increases with increase in surface tension, decrease in density and decrease in weld pool size. While the effect of gravity dominates in natural frequency for larger pools, it is the surface tension that governs the natural frequency for smaller pools.

Modelling of weld pool oscillation during fully penetrated welding of thin plate was described by some researchers. (Maruo and Hirata 1993) The theoretical analysis showed that the mode of oscillation of elliptical weld pool varies as per its shape defined by the ratio of major axis to minor axis. While the oscillation mode kept constant, the natural frequency increased with a decrease in size of weld pool. The natural frequency of primary mode in Hz is modelled as

$$f_0 = \frac{1}{2\pi}\{\left(-gk + \frac{\gamma k^3}{\rho}\right)\left[\frac{\sin h(kh)}{\csc h(kh)-1}\right]\}^{1/2} \quad (2.4)$$

where h is the plate thickness (m), $\gamma =$ is the surface tension of molten metal (N m^{-1}), ρ= is the density (kg m^{-3}) and g= is the gravitational acceleration (m s^{-2}).

2.3.1 Weld pool oscillation due to pulsation of current

Natural frequency of weld pool oscillation can also be found with the help of pulsation of current. Excitation of weld pool using current pulses synchronized with its natural frequency leads to resonance, and thus, the natural frequency may be determined. A phase locked loop system was used for implementing this synchronous weld pool pulsing technique. (Andersen, et al. 1997) The oscillation frequencies of weld pool were detected using an optical sensor, and a model that relates the frequency to geometries of weld pool was developed. The pool width or area was to be measured. The expected resonant frequency from models was compared with the actual resonant frequency to find the weld penetration. Controlling of penetration was made possible with the knowledge of relation between penetration and natural frequency of the weld pool. The weld pool dynamic model was developed as

$$f_1 = \left(\frac{T}{\frac{3}{8}\pi m}\right) \quad (2.5)$$

where f_1 is the frequency for the first mode of oscillation in Hz, T = is the surface tension (N m^{-1}) and m= is the pool mass (kg).

The weld pool was found to possess the dynamic response of a fluid droplet rather than that of a membrane.

Pulsed GMAW has many advantages in terms of weld quality. The process uses a higher peak current to pro-duce one molten droplet per pulse and maintain the arc stability with the help of lower background current. (Pal and Pal 2011) The pulsation increases depth of penetration due to arc oscillation, refines grains in welded zone and causes variation in arc pressure and thus level of aspiration of air in the weld pool, which leads to change in porosity of weldment. (Pal and Pal 2011) Desired quality of weld can be obtained by effectively controlling the pulse parameters.

It has been experimentally verified that the frequency spectrum of arc voltage could be used for detecting weld pool oscillations during the partially penetrated GTAW. (Sorensen and Eagar, Measurement of oscillations in partially penetrated weld pools through spectral analysis 1990) A narrow pulse with sampling beginning on the negative edge of the pulse was selected as the optimum waveform for weld pool excitation signal from several types of current waveforms like constant current, white noise, square wave and pulse waveforms. Arc voltage is proportional to arc length, and hence, the frequency of oscillations of the weld pool could be determined by monitoring the arc voltage. The experiments were conducted with stationary welds on steel plate using helium as shielding gas. Measurements were taken for arc length of up to 13 mm. The relation between weld pool size and its natural frequency of oscillation was observed as inverse, and this relationship is shown in the Figure 2.7.

During pulsed GTAW, the oscillations of larger amplitudes could be imparted to the weld pool using extra current pulses superimposed on the welding pulse, and the frequency of oscillations was used to sense and control the weld penetration. (Aendenroomer and Den Ouden n.d.) At the beginning of pulse and base times, extra pulses were applied. Continuous measurement of arc voltage along with use of fast Fourier transform provides the frequency distribution.

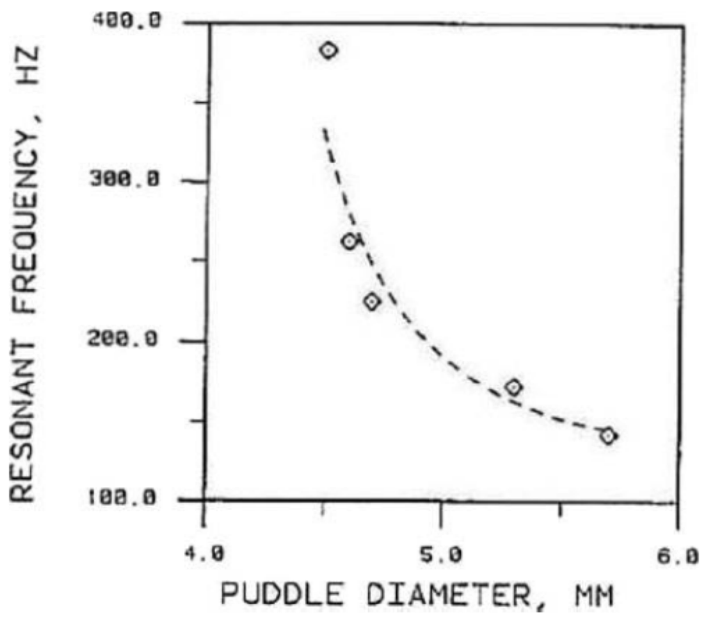


Figure 2.3.a : 7 Resonant frequency versus weld pool diameter for various lengths (Sorensen and Eagar, Measurement of oscillations in partially penetrated weld pools through spectral analysis 1990)

Depending on the welding conditions, the three situations of optimal penetration, under penetration and over penetration could be occurred. One high and one low frequency peak in the frequency distribution lead to optimal penetration. One high frequency peak leads to under penetration, and one low frequency peak leads to over penetration. Thus, the sensing of penetration was made possible by monitoring the peaks in frequency distribution. The in-process control of weld penetration may be carried out by controlling the heat input.

If two different unit pulse conditions are selected for cyclic switchover, the switching frequency was proved to be having substantial effect on frequency of molten pool vibration. (Yamamoto, et al. 1993) The use of two different unit pulse conditions helped to realize low frequency pulsed MIG welding, which was otherwise not possible due to instability in arc behavior. The base material used was Al–

Mg alloy A5052 of 3 mm thickness. The stirring of weld pool due to vibration led to greater grain refinement. Uniform grain refinement was achieved when the switching frequency reached 30 Hz at which amplitude was the highest. The larger the difference between pulsed current values of two unit pulse conditions, the more the grain refinement. Improved grain refinement made the weld less susceptible to solidification crack. Figure 2.8 shows relation between switching frequency and frequency of molten pool vibration. Figure 2.9 shows the relation between switching frequency and amplitude of vibration.

Dynamics of molten weld pool was analyzed for stationary, partial penetration GTAW of 6.4 mm thick cold rolled MS clamped to a copper cooling block. (Renwick and Richardson 1983) A linear constant current source provided the welding power. A short pulse above normal welding current was given to the arc to oscillate the pool. The pulse produced oscillations in the weld pool and thus caused change in arc length, which led to a proportional change in arc voltage, and from the measurement of arc voltage using an oscilloscope, the natural frequency of oscillations was determined. The oscillation frequency of arc voltage was the same as that of the weld pool.

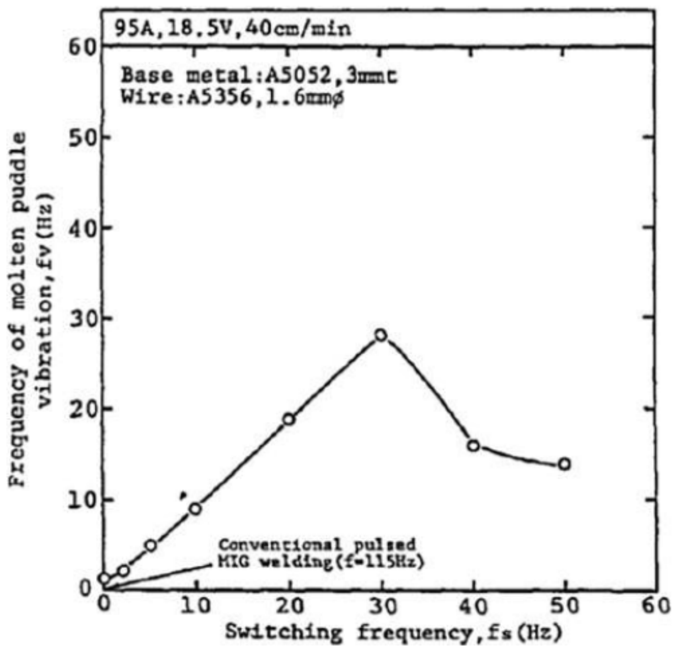


Figure 2.3.b : Relation between switching frequency and frequency of molten pool vibration (Yamamoto, et al. 1993)

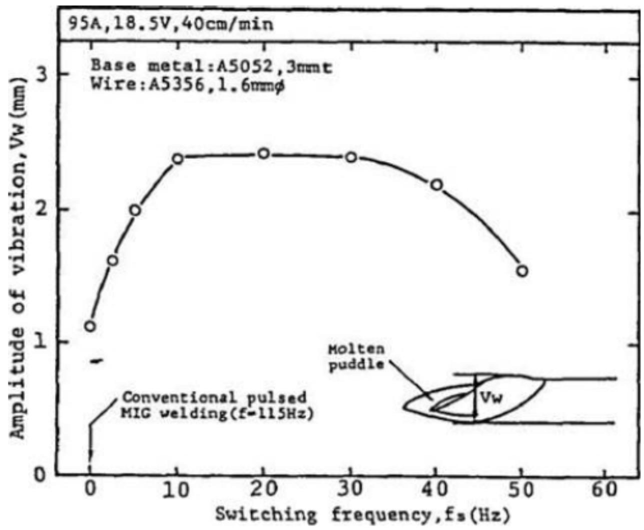


Figure 2.3.c : Relation between switching frequency and amplitude of vibration (Yamamoto, et al. 1993)

High speed films of arc and weld pool taken during the process of pulse welding could be used for ascertaining the pool oscillations and its frequency. It was found that the amplitude of voltage oscillation increased with current.

The natural frequencies of oscillation of stationary weld pools during the GTAW of both Fe 360 mild steel and stainless steel AISI 304 were determined by applying current pulses of approximately rectangular shape. (Xiao and Den Ouden 1990) The oscillation of arc voltage was measured using an oscilloscope, and thus, the oscillation frequencies of weld pools of different sizes were found. Since the natural frequency of oscillation strongly depends on the penetration depth of weld, the same can be used for in-process control of penetration. There was an abrupt transition in the behavior of oscillation frequency for a shift from partial penetration to full penetration. When the bottom diameter of the weld pool was relatively small, the weld pool acted similar to that of partial penetration, and when it was large, it followed a different mode of oscillation. For partial penetration, the natural frequency of oscillation varied between 100 and 400 Hz and decreased with D in a manner of $D^{-3/2}$, where D was the diameter of the weld pool. For full penetration, it varied from 25 to 40 Hz and decrease as D^{-1}.

Twin arc TIG welding is another method to excite the weld pool by injecting ultrasonic vibrations (Wang and Hong 2010) in which welding may be performed in combination with ultrasonic arc and ordinary dc arc. Two separate power sources were responsible for producing these two arcs and the ultrasonic arc injected ultrasonic vibrations into the common weld pool. Direct current arc remained as the main source of heat supply as the heat from ultra-sonic arc was smaller. The ultrasonic arc is produced by combining dc with dc pulse current (PC) of ultrasonic frequency. The experiments on steel 304 resulted in thinning the microstructure of weld besides the improvement in tensile strength and welding efficiency. The presence of ultrasonic vibrations in the molten pool was ascertained using an ultrasonic receiver probe, which, when employed near the pool with the help of a couplant, produced piezoelectric signals.

Weld pool oscillations due to ac pulses during the full penetration GTAW of AZ31 magnesium alloy resulted in grain refinement and led to improvement in fusion zone hardness, tensile strength and ductility. (Kishore Babu and Cross 2012) In addition to variation in temperature gradient and improved solidification rate, the oscillation of weld pool was also cited as the reason for the significant grain refinement. When the pulsed current was applied near to the natural frequency of oscillation of the weld pool, it started to resonate. With resonance, the amplitude was higher, and the grain refinement occurred also was higher. Oscillation of weld pool was understood to have favored the fragmentation of dendrites. Columnar grains were mostly prevented from forming equiaxed grains. Both the amplitude and frequency were import-ant parameters for grain refinement. The values of pulse frequency applied were 2, 4, 6, 8 and 10 Hz at a travel speed of 4.16 mm s^{-1} and arc voltage of 11.5 V.

Analysis of weld pool oscillations during GTAW of mild steel Fe 360 with travelling arc was conducted by some researchers. (Xiao and den Ouden 1993)Application of short current pulses made the weld pool oscillating, and from the oscillation of arc voltage, the amplitude and frequency of weld pool oscillations were determined. The torch was kept fixed, and the test plate was moved. The weld pool was elongated, and there was a shift for welding arc from the geometric canter of pool to front edge of pool. The natural frequency of oscillations could be determined based on the phenomenon of resonance. Both the partially and fully penetrated pools had different modes of oscillations. Pulse frequency for partial penetration welding varied from 5 to 25 Hz and that for full penetration was 12.5 Hz with the frequency at transition from partial to full penetration being 12.5 Hz. An abrupt change in frequency was observed with the transition from partially to fully penetrated welds, and this could be used for the in-process control of weld penetration. Figure 2.10 shows this abrupt change in frequency. The higher the size of pool, the lower the natural frequency of oscillation.

Another technique for employing PC is double pulse GMAW in which one low frequency PC is superimposed on a high frequency current pulse, and the oscillation of the weld pool depends on thermal pulse frequency (low frequency pulse). (Liu, Tang and Lu 2013)

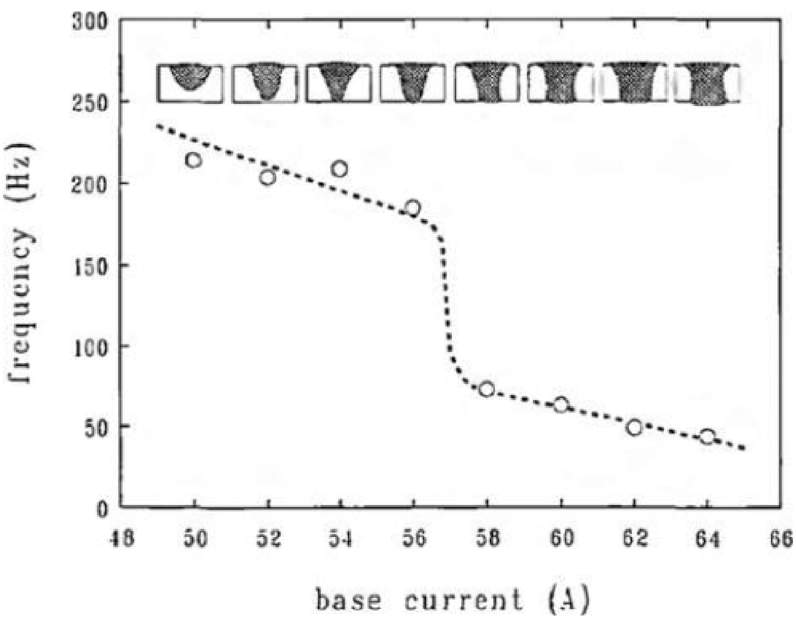


Figure 2.3.d : Oscillation frequency and weld pool geometry as function of base current (Xiao and den Ouden 1993)

Appropriate low frequency pulse value should be selected for having adequate amplitude of weld pool oscillation. The high frequency pulse controls the droplet transfer and thus influences the weld penetration.

2.3.2 Weld pool oscillation through waveguide

Ultrasonic vibrations as applied to the weld pool with the help of a waveguide could change the structure of weld, and these changes were dependent on the wave phase. (Krajewski, et al. 2012)The base material was 2017A aluminum alloy, and the effect of vibration was evident both in TIG and MIG welding. The experimental set-up consisted of welding torch, linear manipulator, waveguide, ultrasonic transducer and concentrator. The 2017A aluminum alloy waveguide was in the form of a cylinder of diameter of 0.045 m and length of 0.254 m. The vibration frequency was 20 kHz. The length of waveguide was equal to the wavelength of 1l with respect to the 20 kHz frequency. At the maximum displacement of vibration wave, face width and weld penetration depth increase in TIG welding and face width decreases in MIG welding.

2.3.3 Weld pool oscillation using pulse shielding gas (PSG) oscillating method

The PSG oscillating method is an alternative to PC method to excite oscillations in the weld pool of TIG arc welding of the thin steel plate. (Ju, Suga and Ogawa May 2002) Apart from PC in which the current pulses are applied to create oscillation in weld pool, in PSG oscillating method, the shielding gas does the duty. An arc sensor detects the oscillations of weld pool, and its natural frequency of oscillation is determined. Since there is a relation between pool geometry and its natural frequency, the penetration of weld can be determined. The PSG method was stated to be easier and better compared to the PC method in terms of amplitude of oscillation and robustness in measurement of frequency. A system for controlling the weld penetration by controlling the welding current with respect to oscillation frequency was constructed. Figure 2.11 shows the welding torch for PSG method.

2.3.4 Weld pool stirring using mechanical stirrer

Mechanical vibrations were successfully introduced into the molten pool with the help of a stirrer during SMAW of 10 mm thick austenitic stainless steels to form butt joints. (Singh, Kumar and Garg 2012)

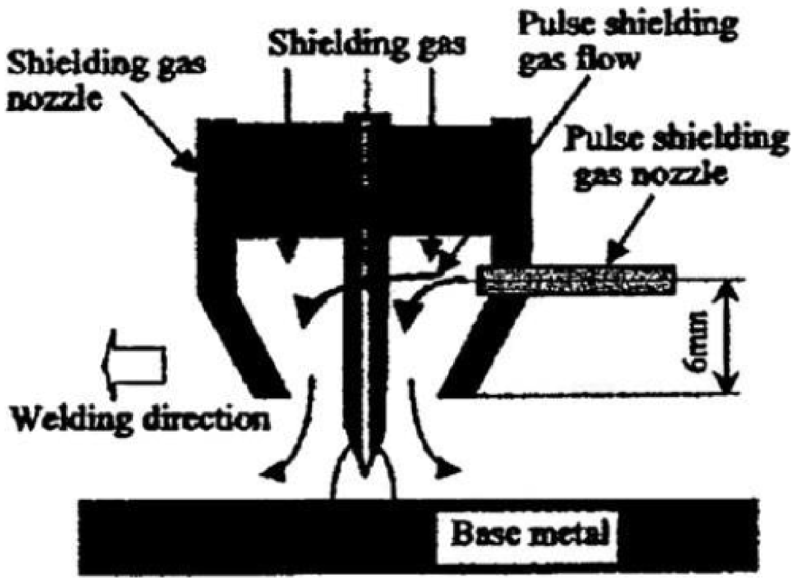


Figure 2.3.e : Welding torch for PSG method (Ju, Suga and Ogawa May 2002)

The stirrer, which was a throated tungsten rod having melting point of 3410uC, trailed behind the welding arc along the length of weld producing high frequency and low amplitude vibrations in weld pool through stirring. The resulted weld metal had more micro indentation hardness and finer microstructure. The welded joint had higher yield strength and tensile strength and maintained the same ductility.

2.3.5 Weld pool oscillation through vibrating filler material

Ultrasonic vibrations could be transmitted to the weld pool through the vibrating filler material. (Watanabe, et al. 2010) In one such experiment, the excitations generated by an ultrasonic transducer were amplified through a horn and passed on to a guide tube through which the filler metal was fed to the weld pool. The filler metal vibrated perpendicular to the weld direction at a frequency of 19 kHz. The work-piece material was high purity ferritic stainless steel, and full penetration bead on plate GTA welds were made. Formation of equiaxed grains was enhanced in the central region of weld metal by ultrasonic vibration. The more such grains formed, the more was the welding speed. Tensile strength and tensile fracture elongation of weld metal were higher for welds with vibration.

2.4 Molten droplet oscillation

The mode of metal transfer has a lot of influence on the quality of welds. Pulsed current GMAW is a way to achieve controlled metal transfer. An analytical model was developed for explaining the droplet oscillation and detachment process in pulsed current GMAW. (Wu, Chen and Li 2004) (Chen, et al. 2006) In pulsed GMAW, the pulse cycle comprises of two periods, droplet growth period and droplet detachment period. During the pulse-on time, droplet grows, and when the current falls to base value, the detachment period starts. The sudden fall in the current reduces the electromagnetic force acting on droplet making it oscillating along the vertical direction. The peak value of current is switched on at a suitable time so as to make use of the downward momentum of droplet in its detachment. The timing of excitation is so important that both the downward movement of droplet and its sufficient downward momentum are ensured. Hence, the droplet oscillation actively helps in achieving controlled metal transfer. It was learned from the model that the level of excitation and its timing have greater effect on droplet detachment and thus the metal transfer. The much sought after mode of one droplet per pulse may be obtained, by adjusting these two parameters, at a peak current lower than the transition current. Thus, the modified pulsed current GMAW ensures a far better controlled metal transfer. (Chen, et al. 2006)

In general, the arc voltage is directly proportional to arc length in GMAW. But in pulsed GMAW, because of the droplet oscillation, this relationship may not be correct always as reported by some researchers. (Yudodibroto, et al. 2006) In an experimental study, bead on plate welds were made on MS plates, using a constant current power source. Frequencies of droplet oscillations were measured both using a high speed video camera and through analysis of arc voltage signals. The findings were compared with that predicted by an analytical model developed based on spring mass system. The three methods gave matching values of frequency of oscillation for smaller sized droplets. For larger droplets, the value from analysis of arc voltage signal differed from other two and was higher than them. It was concluded that the oscillation of droplet affects the behavior of arc thereby deviating from the expected linear relationship for them.

A numerical model was developed for explaining the droplet oscillation and detachment phenomena in pulsed GMAW. (Hirata, et al. 2007) The model explained that the natural frequency of molten droplet decreases with increase in droplet size. The droplet detachment is largely assisted by periodical forces adjusted to create resonance in oscillation of droplet. The numerical model was validated by experiments using water drops.

2.5 Oscillation of welding arc

The oscillation of welding arc was proved to be another method of generating agitations in weld pool. A two-dimensional mathematical model was developed to study the effect of electromagnetically oscillated arc on the microstructure and temperature distribution of bead on plate welds on thin tantalum sheets made through GTAW. (Grill 1981) The associated experiment was conducted in a glove box in which the pressure was maintained slightly above its atmospheric value. The arc was transversely oscillated up to a frequency of 25 Hz with maximum amplitude of 6.5 mm. In tune with the arc oscillations, oscillations in temperature were observed in the weld zone. Owing to the nucleation mechanism because of the large temperature oscillations, the grain structure was refined considerably in the fusion zone. When the frequency of oscillation of arc crossed 20 Hz, the amplitude of temperature oscillation decreased. The amplitude of temperature oscillations were found to be increasing with increase in amplitude of oscillations of welding arc up to a certain value after which it showed a behavior of independence.

Magnetic oscillation of the arc was achieved using a four-pole magnetic arc oscillator. (Kou and Le 1985) Direct current straight polarity GTAW was carried out on 5052 aluminum alloy sheets of 1.6 mm thickness with pure argon as the shielding gas. Constant arc voltage was maintained during welding with the help of an automatic arc voltage controller. Circular, transverse and longitudinal types of arc oscillations were produced using the four- pole magnetic arc oscillator for which the frequency range was 0.9–35 Hz. A digital oscilloscope measured the frequency of oscillation, and a split anode measured the amplitude. Both at low frequency range of *1Hz and high frequency range of *20 Hz, reduction in solidification cracking was observed, and the alteration of grain orientation in the former case and grain refinement in the latter case were attributed to be the reasons for it. At the intermediate frequencies where neither alteration of grain orientation nor grain refinement has happened, the solidification cracking was severe. Grain refinement and reduction in solidification cracking occurred at circular, transverse and longitudinal oscillations at high frequencies. Alteration of grain orientation and reduction in solidification cracking happened for all the modes of oscillation at low frequencies except longitudinal one.

In a narrow gap GTAW of AISI 304L stainless steel plates, the electromagnetic arc oscillation did not have any influence on lateral fusion of joint, but it reduced the axial fusion. (Starling, et al. 1995) However, the oscillation increased the concavity and improved bead shape. With the reduction in gap width, the tendency to form undercutting was increased. Special power supply was used for the electromagnet.

Transverse oscillations of arc produced with the use of an alternating external magnetic field in GTAW of a–b titanium alloy could make considerable amount of grain refinement in the fusion zone. (Sundaresan and Ram 1999) The process was of autogenously, full penetration and bead on plate. The electromagnetic arc oscillation equipment consisted of a water cooled electromagnetic probe mounted on to welding torch and a control unit. The amplitude and frequency of the square wave current signal were independently adjusted during the experiment. Thus, the alternating magnetic field also was adjusted accordingly. Welding was performed within the frequency range of 1–20 Hz and at 0.6 mm amplitude. Optimum values for amplitude and frequency were found at which the grain refinement was the maximum. The specimens made through electromagnetic oscillation of arc were more ductile than the ordinarily welded specimens even after the post-weld heat treatment.

By exerting high frequency electric signal to welding circuit, the welding arc in CO2 gas shielded arc welding of mild steel plates was modulated to emit ultrasonic energy into the molten pool. (Zhang and Zou 2010) The experimental set-up is shown in Figure 2.12.

To monitor ultrasonic emission and record acoustic signal, a transducer, oscilloscope and PC data collection card were employed within the system.

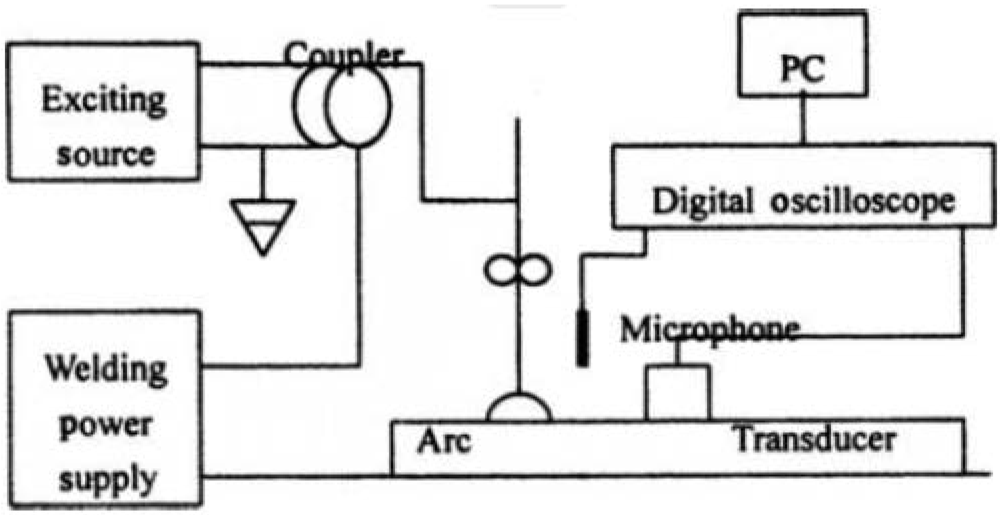


Figure 2.5.a : Experimental set-up for emitting ultrasonic energy through welding arc (Zhang, et al. 2009)

The frequency of arc ultrasonic substantially helped in grain refinement of welds. The phenomenon of resonance was observed, and the non-resonant frequencies could not do much towards grain refinement.

Alternating current pulsing, magnetic arc oscillation and the combination of these two were proved to be beneficial to improve grain refinement in autogenously GTA welds of 2219-T87 plates. (Rao, et al. 2005) Peak and base currents were 180 and 60 A respectively in pulsed bead on plate welding with frequency ranging from 2 to 10 Hz. Frequency within the range of 2–10 Hz and peak current of 120 A were used in magnetic arc oscillation. For the PC+AO, respective parameters remained the same with peak current being 180 A. Linear and elliptical modes of arc oscillations were employed during AO and PC+AO methods. All the above techniques led to fine equiaxed grains in welds. Frequencies of oscillating arc and PC were found to be key players in achieving grain refinement. The three processes were effective in increasing tensile properties and ductility of the welds.

The structure of weld made through a process of vibration welding along with arc oscillations can possess orientation in preferred directions. (Kuo, et al. 2008) A mass eccentric vibrator helped to apply mechanical vibration during autogenously GTAW at a resonant frequency of 47.3 Hz and amplitude of 0.203 mm. The parameters at welding were 180A, 13V and 20mmmin21. The speed of oscillation was 3.3 mm s21 for 35 mm width. The vibration arc oscillation welding was superior to vibration less arc oscillation welding in the aspects of micro structure. Secondary dendrite arms were observed rarely during vibration welding. However, those dendrites with an orientation parallel to vibration grew easily and strongly in vibration welding. This established that the vibration welding had more preferred orientation than one without vibration.

Significant grain refinement was reported for the weld made of Inconel 690 when it was welded in constant current GTAW with a filler material of Inconel 52M under the conditions of circular magnetic arc deflection. (Lim, et al. 2010) The oscillation device consisted of a magnetizing coil with two pole pairs, which surrounded the tungsten electrode when fitted to the torch. Magnetic poles near the welding arc generate orthogonal magnetic fields, which deflected the arc in circular or oval patterns. Phase and magnitude of these magnetic deflections were so adjusted that the arc was rotated in a circular path with specified frequency and amplitude. The circular arc motion stirred molten metal in pool through corresponding rotation of electromagnetic force field induced by arc current. A microstructure of small, equiaxed grains was observed at a stirring frequency of 7 Hz.

The shape of indirect arc could be modified using applied magnetic field in twin wire indirect arc gas shielded welding. (Zhang and Zou 2010) Only little current passes through the base material, and the channel for current is along the ‘U’ path in twin wire indirect arc welding. Figure 2.13 shows the scheme of indirect arc.

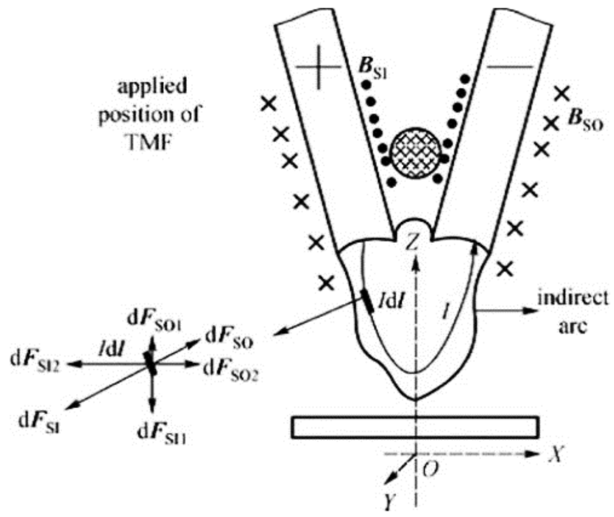


Figure 2.5.b : Scheme for indirect arc (Zhang and Zou 2010)

Resistance to hot cracking was found to be improved in transverse mechanically arc oscillated (TMAO) autogenous AA2014T6 welds. (Biradar and Raman, Investigation of hot cracking behavior in transverse mechanically arc oscillated autogenous AA2014 T6 TIG welds 2014) A mechanical oscillator generated transverse arc oscillation by the movement of a single axis slide. The frequency of oscillations was limited to 10 Hz.

The process with amplitude of 0.9 mm and frequency of 0.5 Hz resulted in significant reduction of tendency for hot cracking. Increase in hot cracking resistance was due to the grain refinement happened because of the mechanical agitation and increase in cooling rate due to arc oscillation. Liquation crack in partially melted zone was completely eliminated and this was because of reduced extent of grain boundary liquation and subsequent reduction in the width of partially melted zone. Change in the morphology of bead due to arc oscillation led to uniform residual tensile strains, which also helped to reduce the tendency for hot cracking.

Transverse mechanically arc oscillated caused grain refinement in Al–Mg–Si alloy TIG welds also. (Biradar and Raman, Grain refinement in Al–Mg–Si alloy TIG welds using transverse mechanical arc oscillation 2012) The same mechanical oscillator as described above was used here. The experiments were conducted at fixed amplitude of 1.4 mm and at three different frequencies of 0.28, 0.92 and 1.5 Hz. Frequency was the key parameter in getting refined grain for welds. The higher effective welding speed in TMAO improved the cooling rate, which led to less net linear heat input producing finer grains. The mechanical properties of weld like yield strength, UTS and percentage elongation were improved due to the grain refinement caused by arc oscillation.

Transverse mechanically arc oscillated produced finer grains in welds made of mild steel in GTAW. (Mahajan, et al. 2012) Welding arc was oscillated at a frequency of 0.7 Hz and amplitude of 1.5 mm with the help of a mechanical oscillator. Arc gap of 3 mm was maintained with a direct current electrode negative power source. While columnar grains appeared in welds made without TMAO process, smaller equiaxed grains were observed in those made with process of TMAO. Higher strength and ductility were reported for welds made with oscillated arc due to higher grain refinement. The process of TMAO caused less hardness for weld metal and higher hardness in HAZ. The TMAO increased the cooling rate in weldment, and the same affected the properties of welded joint.

A swinging arc system for narrow gap GMAW was designed (Wang, et al. n.d.) by which high quality welds were obtained at low cost. In the newly designed torch, a motor of hollow axis turned a micro bent conductive rod for swinging the arc as shown in Figure 2.14.

The process may be used for better penetration onto the sidewalls of the groove. Convenient weaving modes may be selected by adjusting the turning angle and direction of motor.

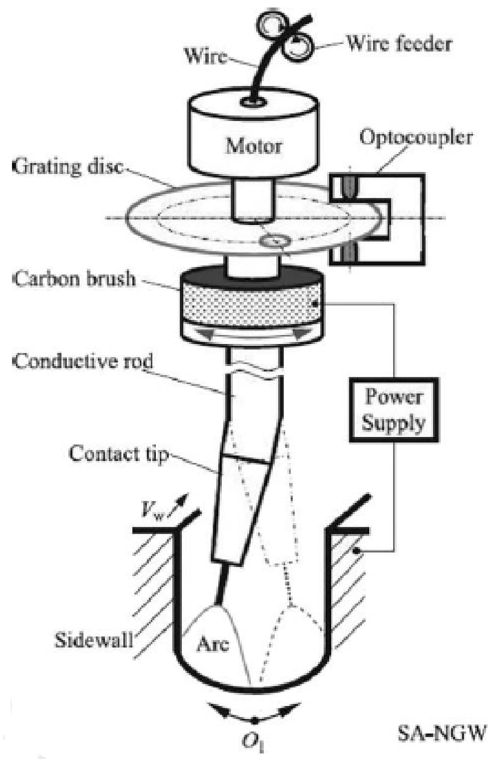


Figure 2.5.c : Swing arc system for narrow gap GMAW process (Wang, et al. n.d.)

Swing frequency, swing amplitude and at sidewall staying time are the parameters that may be adjusted for each mode of weaving. It was found that, with the increase in frequency of swing and staying time, the depth of penetration of grove sidewalls and surface curvature of weld increase.

2.6 Vibration of welding electrode

Supplying the vibration energy to electrode is another method to achieve agitation in the welding. The vibration may be given both in TIG and GMAW types of welding, and the resulting impact may be different for them. Electrode vibration has succeeded in improving the metal transfer rate in GMAW. As pointed out by some earlier researchers in GMAW, the vibrating electrode cannot simply give sufficient mechanical energy to directly melt additional metal. As per them, the energy previously used to overheat the drops is available to melt additional metal with vibrating electrode. Intelligent control of metal transfer, and thus the weld quality, is possible with duly adjusting the parameters of electrode vibration.

The ultrasonically vibrated welding electrode could produce more arc pressure in TIG welding. (Sun, et al. 2008) The electrode vibrated axially, and the vibrations were passed on to weld pool through arc plasma. The ultrasonic vibrations created using an ultrasonic generator was transmitted to welding torch through a mechanical coupling and bead on plate welding was carried out on stainless steel pieces. The study revealed that there was an improvement in arc pressure distribution in a way favorable to the process of welding, and the radial distribution of arc pressure was close to Gaussian distribution. The process could increase fusion zone area, weld depth/width ratio and weld penetration depth in comparison with conventional TIG welding.

Figure 2.15 shows the scheme of ultrasonic vibrated welding torch GMAW system. Ultrasonic assisted GMAW method was developed and applied to bead on plate welding of 8 mm thick mild steel pieces. (Fan, et al. 2010)

The welding set-up included a specially designed hybrid welding torch, which vibrated axially, welding power supply and ultrasonic power supply. The welding torch, as a whole, consisted of ultrasonic transducer to develop mechanical vibrations, horn to amplify the vibrations and a provision to feed electrode wire through a centrally made hole. Here, the mechanism was such that the workpiece remained stationary and the torch got vibrated. The electrode wire supplied through the central hole did not get vibrated. The ultrasonic wave radiated from the end of horn and reflected from the surface of workpiece. An acoustic radiation field was created together by the incident and reflected waves. The acoustic radiation wave improved the metal transfer by affecting the nature of droplet detachment. (Fan, et al. n.d.) In comparison with the conventional process, the arc length was compressed. The mode of metal transfer changed to ‘short circuiting transfer’ from ‘globular transfer’, and weld surface was significantly different.

2.7 Concluding remark

After studying the literature review, it has been found that several experiments have been done to find out the variation of results between oscillated and non-oscillated welding but until now, a few oscillation assisted welding experiments has been done using ranges of different parameters. Here, some input parameters like vibration amplitude, vibration frequency, welding speed and electrode angle are selected to analyze the variation in welded joint. For analyzing the results, output parameters – hardness, bending strength, deposition rate and dilution are selected. Those parameters are chosen because using these parameters no study has been done yet. In this study, main goal is to analyze the changes of mechanical properties of the joining section of the metals by giving the oscillation on the base plate.

Chapter 3 Methodology and Development of Experimental Setup

3.1 Introduction

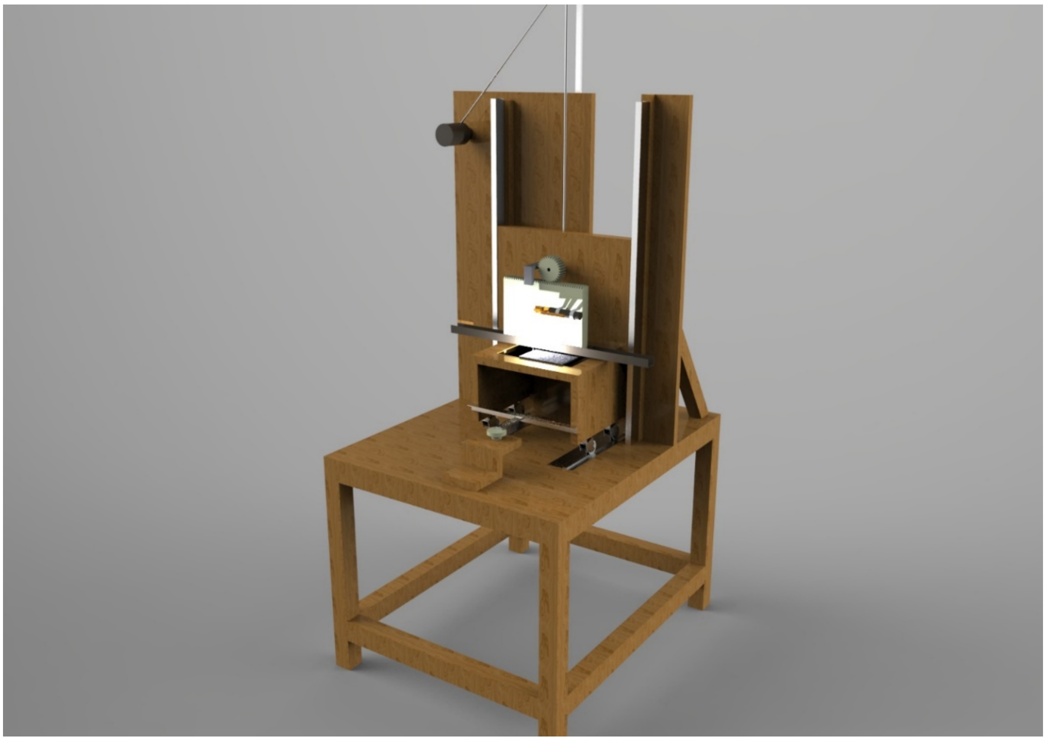
The scope of this chapter is to establish a new concept to welding process by introducing vibration to the job piece. Any amount of frequency is not suitable for welding because large amount of frequency will not help. There is a range of frequency level (80 to 400 Hz). Within this amount of frequency, joining of the metal gives the good amount of mechanical properties. Therefore, experiments are conducted within this range. For providing this frequency, an experimental set up has been established. Varying some of the input parameters like amplitude, frequency, welding speed, welding angle etc. some output parameters like hardness, bending load, bending stress are found. Those results are better than without oscillation of the base table.

3.2 Concept

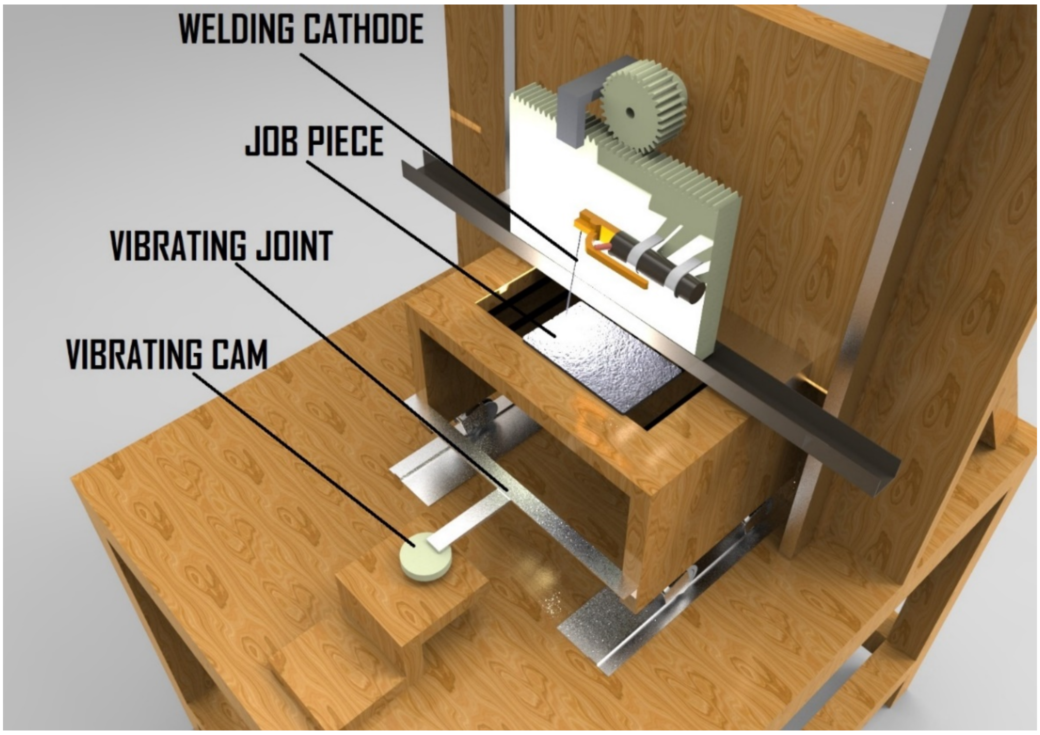
Welding is usually done to join two metals but the strength of the joining point depends on the welding quality. Welding quality depends on: hardness, bending strength, dilution rate, deposition rate etc. Hardness of a joining point is one of the important factor. Because it represents the amount of porosity is into the joining point. Porosity is obviously not good for any welded joint cause it shows how weak the joint is. Here oscillation on job piece has a good effect on the welded joint to reduce the amount of porosity. Bending strength is also an important property in this case. Because it represents the strength of the welded joint. As oscillation has a great effect on improving, the bending strength of welded joint by increasing the penetration it is decided to compare variation of the data with and without oscillation. Dilution rate is defined as the ratio of the diluted metal and the welded metal. Deposition rate is defined as the welded metal is deposited on the joining point per second. So the dilution rate and deposition rate is more so as the welding strength. For increasing those two, our thinking is to use oscillation of the base plate of welding process because if the oscillation is given to the base plate then more metal will enter into the joining point more than without oscillation and deposition rate per area will be high. If the deposition rate per area is high then dilution rate will be also high. Welding speed is also a vital parameter because it will control the deposition rate. Welding angle has an effect on deposition rate too. Therefore, the experiments are conducted by using those parameters to check the welding strength of the joining point.

3.3 Details of the setup

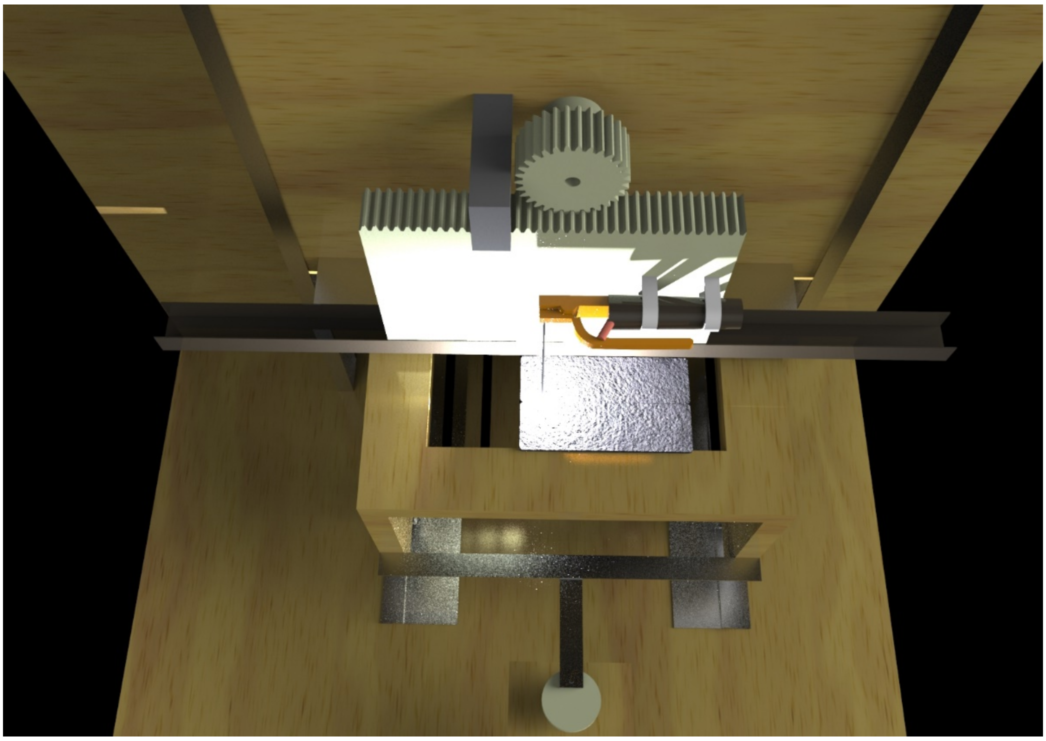
Experimental setup is an important part of an experiment based research but to do that virtual setup should be made first. Here virtual setup means design the experimental setup in software and analyze its feasibility. That is why automatic setup has been designed in "SOLIDWORKS" shown in Figure 3.1 (a) (b) (c). Then it is analyzed and selected for this experiment.



(a)



(b)



(c)

Figure 3.3.a : SOLIDWORKS design of (a) experimental setup (b) vibration system (c) welding process

First, a wooden frame of the experiment has been made. This wooden frame includes a table and a large plate, which is vertically set on the table. On the wooden plate, there are two pulleys. By this connection, that wooden plate can move upward and downward. On that plate, there is a pinion. A rack is set on an aluminum frame which is connected with the wooden frame. Rack and pinion are meshed together That is why this connection can move back and forth. On that plate, welding holder is joined. The vertical wooden plate has space in front of it, where the small wooden base table is kept. This wooden base table has a square hole where metallic rods are placed. At that place, job piece will be kept for the experiment. Metallic rods are placed over there because earthing point should be maintained for welding. Sidewall of the small base table are connected with two springs with main table. The small base table has four wheels and those wheels can roll on two rail lines. One vibration device is established in front of that small base plate. The experimental setup is shown in Figure 3.2 below:

Figure 3.3.b : Experimental setup

3.3.1 Axis

For the experiment, two axes movement are necessary: X- axis and Y- axis. On the vertical wooden plate contains two rails, which hold a wooden plate. This plate can move up and down. This Y – axis movement is for starting and ending of the welding process. At first, this wooden plate remain on top of its position. When the welding process starts it moves downward to the job piece and moves according to a constant speed comparing to melting speed of the filler rod. And at the X – axis, another wooden plate can move back and forth. This speed is also maintained at a constant speed of the melting speed of that filler rod so that at the same time the filler rod can move downward and forward at a constant speed to complete the welding process. After completing, those wooden plates move upward and backward for another process.

3.3.2 Vibration

There is a vibration device, which provides the vibration to the base table. By using a software this vibration device is controlled. Using this software different amount of vibration frequency can be provided to the base table.

3.4 Methodology

This experiment of welding process is done to analysis the change of the mechanical properties of welding joining point. At first, doing some literature review it has been selected that which of the parameters are have great effect on the joining point of welded materials. Those selected input parameters are:

- Vibration amplitude
- Vibration frequency
- Welding speed
- Electrode angle

3.4.1 Input parameters

Vibration amplitude is set up with a dial gauge shown in Figure 3.3. As previously discussed in the "Details set up" section that there is a small wooden table on the main table. This small table holds the job pieces. To provide the vibrational amplitude to the job piece, it is set like that; it should be provided to the small wooden table. Because when the job piece moves, this small table moves too. Actually, the vibration passes to the job piece through that table.

Figure 3.4.a : Dial Gauge

Vibration frequency is provided to the job pieces by a vibration system is shown in Figure 3.4. This vibration system is mainly a motor with a shaft. That motor is controlled by a simple coding of a software named "ARDUINO". This coding of this software is that with the help of a computer vibration frequency can be changed within a range. There is switch connection with this device so that it is easy to switch on the device when vibration is necessary.

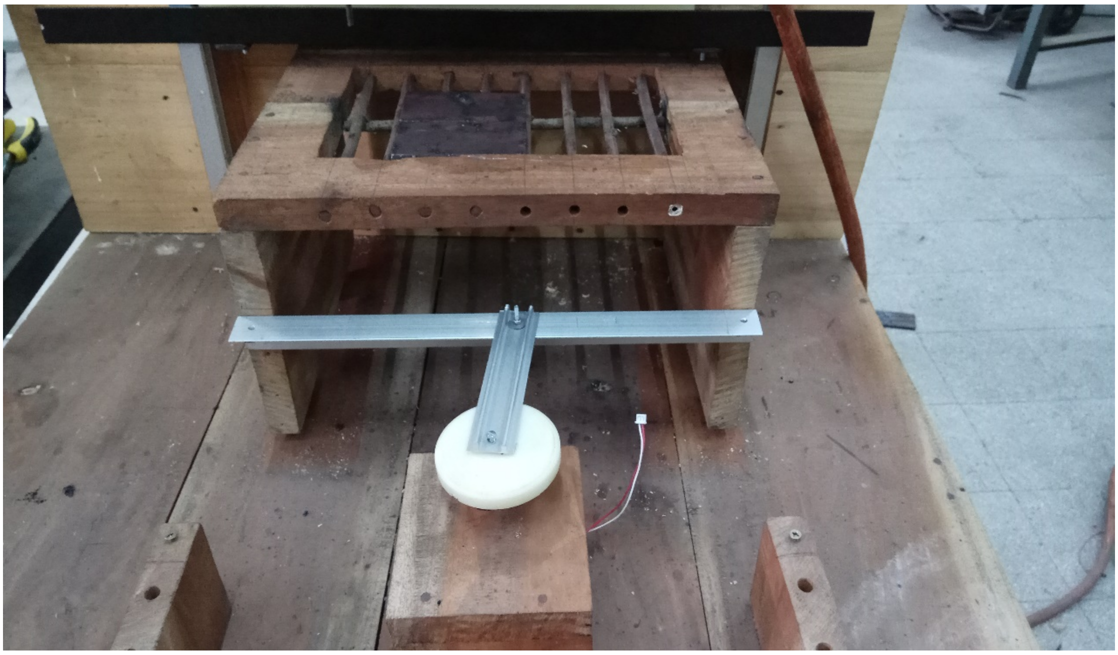


Figure 3.4.b : Vibration system

Welding speed is measured here in mm/second. By giving different speed, the changing has been analyzed.

There are many size of filler rod but particularly for this experiment, 2.5 mm filler rod is used which is shown in Figure 3.5.

Figure 3.4.c : Filler rod

In this experiment, first the whole design is done in “SOLIDWORKS” software shown in Figure 3.6.

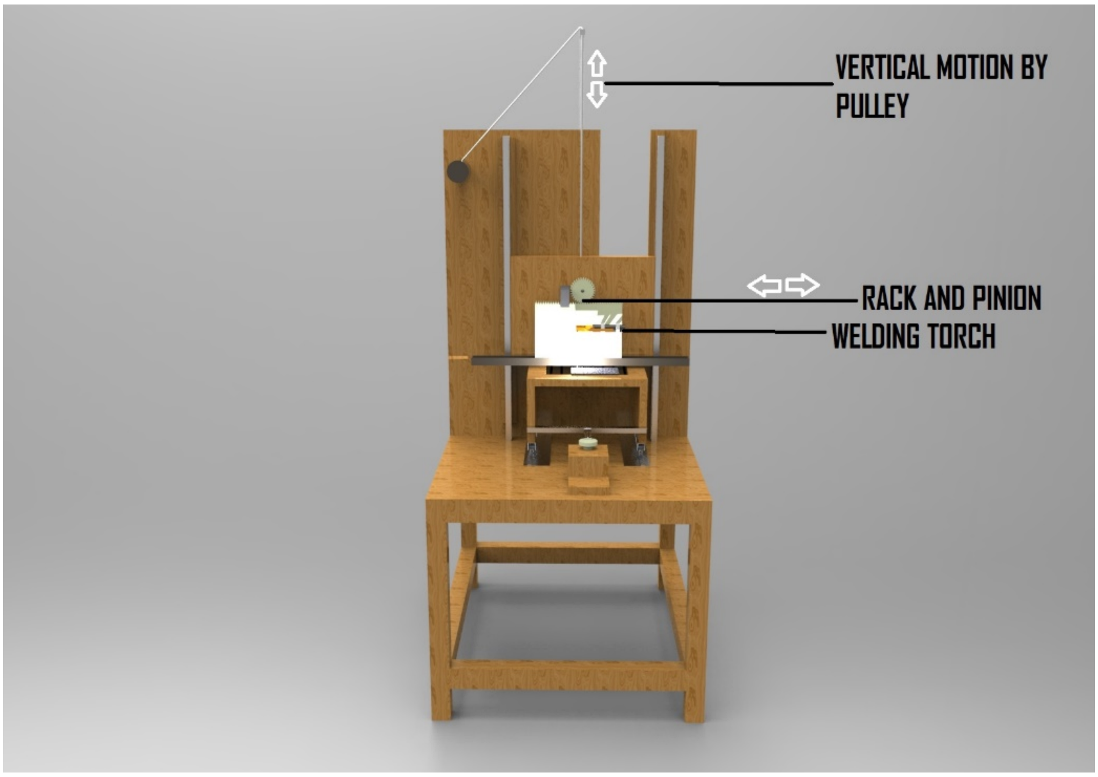


Figure 3.4.d : Software design in SOLIDWORKS

Then according to that design, wooden frame of that is made and checked the feasibility. After doing some modification of the very first design, the frame has become ready for the experiment. Mild steel job pieces are selected. First, the job pieces are cut in the same dimension. Every job pieces is 135 mm long and 40 mm in width. For the welding process, every one of them are grinded with the grinding machine in Figure 3.7. Then the welding process is done.

Figure 3.4.e : Grinding machine

V_A =1.0µm, V_F =125 Hz,

W_S = 1mm/sec, E_A=15^0

(a)

V_A =1.5µm, V_F =150 Hz,

W_S = 2mm/sec, E_A=25^0

(b)

V_A =2.5µm, V_F =175 Hz,

W_S = 1.5mm/sec, E_A=20^0

(c)

V_A =2.0µm, V_F =200 Hz,

W_S = 2mm/sec, E_A=15^0

(d)

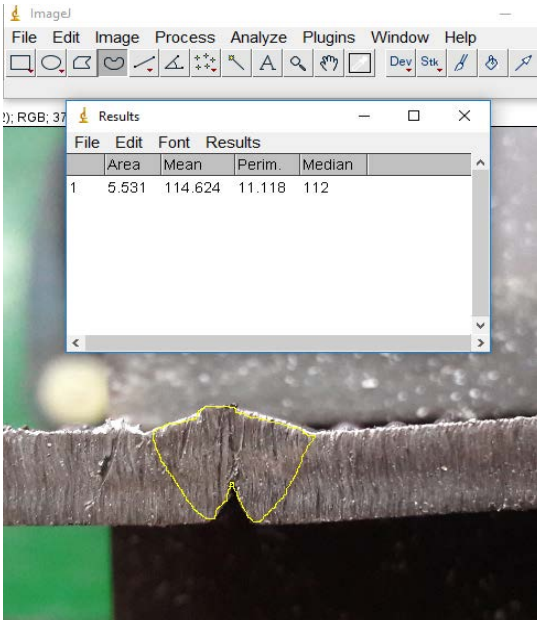
Figure 3.4.f : welding joining point (a) (b) (c) (d)

While the welding process was running then for every experiment deposition rate was calculated.

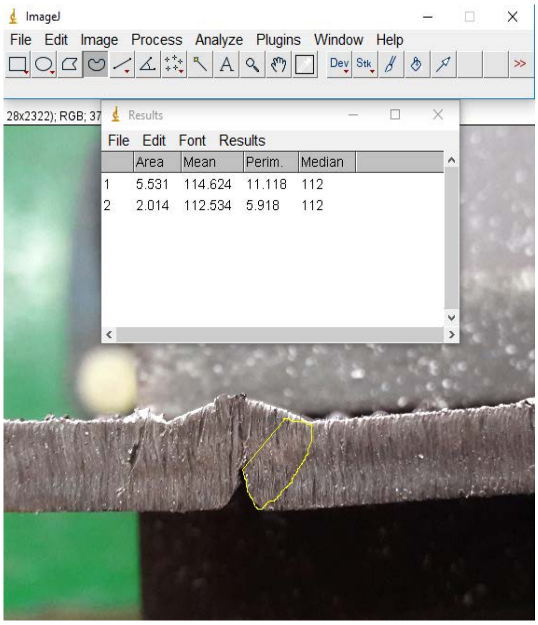
After completing the welding process shown in Figure 3.8 (a), (b), (c), (d), those job pieces are taken to analyze for the changing of the mechanical properties of the joining point. With the help of a Rockwell Hardness testing machine in Figure 3.9, every specimen is tested and noted down. Then by using a Universal testing machine in Figure 3.10, bending strength of every one of them are calculated.

Figure 3.4.g : Rockwell hardness machine

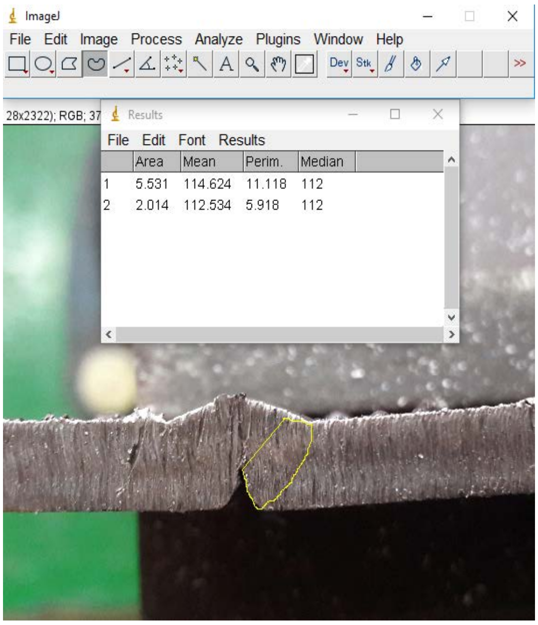
Figure 3.4.h : Universal testing machine



(a)



(b)



(c)

Figure 3.4.i : Percentage of Dilution calculation in “ImageJ” software.

Dilution calculation is one of the difficult part in this experiment. Because this small amount of area cannot be easily calculated. For this calculation, another software “ImageJ” has been used. After taking the picture of all specimens, those are imported in this software one by one and calculated the percentage of dilution in the welded area shown in Figure 3.11(a)(b)(c).

3.4.2 Central Composite Design (CCD)

The experimental design techniques commonly used for process analysis and modeling are the full factorial, partial factorial and central composite rotatable designs. A full factorial design requires at least three levels per variable to estimate the coefficients of the quadratic terms in the response model. Thus for the four independent variables 81 experiments plus replications would have to be conducted. A partial factorial design requires fewer experiments than the full factorial. However, the former is particularly useful if certain variables are already known to show no interaction.

An effective alternative to the factorial design is the central composite design (CCD), originally developed by Box and Wilson and improved upon by Box and Hunter. The CCD gives almost as much information as a three-level factorial, requires much fewer tests than the full factorial and has been shown to be sufficient to describe the majority of steady-state process responses.

The number of tests required for the CCD includes the standard 2k factorial with its origin at the center, 2k points fixed axially at a distance, say b, from the center to generate the quadratic terms, and replicate tests at the center; where k is the number of variables. The axial points are chosen such that they allow rotatability, which ensures that the variance of the model prediction is constant at all, points equidistant from the design center. Replicates of the test at the center are very important as they provide an independent estimate of the experimental error. For three variables, the recommended number of tests at the center is six. Hence the total number of tests required for the four independent variables is 2^3 + (2 * 4) + 6 = 30. The experimental layout for the four independent variables using CCD is shown in Table 3.2

3.4.2.1 Ranges of the parameters

Design Expert 7.00 is a software, which is used to determine the number of experimental tests by using the number of input parameter. This software helps to determine the model equations. This model equation generates the required graphs and those graphs shows the effects of the input parameters on the joining point. Table 3.1 represents the input parameters with ranges:

Table 3.1 : Input parameters with ranges

Parameters	**Symbols**	**Levels**				
		$-\sqrt{2}$	-1	0	$+1$	$+\sqrt{2}$
Vibration amplitude (µm)	V_A	12.9	15.0	20.0	25.0	27.1
Vibration Frequency (Hz)	V_f	79.29	100.0	150.0	200.0	220.7
Welding speed (mm/sec)	W_S	1.4	2.0	3.5	5.0	5.6
Electrode Angle (°)	E_A	11.9	15.0	22.5	30.0	33.1

Each numeric factor is varied over 5 levels: plus and minus alpha (axial points), plus and minus 1 (factorial points) and the center point. If categorical factors are added, the central composite design will be duplicated for every combination of the categorical factor levels.

Non center point = 24

Center point = 06

Total Run = 30

Here, alpha = $\sqrt{2}$

Table 3.2 : Total number of tests for the experiment with oscillation

No. Of Study	Input parameters				Output parameters (Experimental)			
	V_A	**V_F**	**W_S**	**E_A**	Hardness (HRC)	Bending Strength (MPa)	Deposition rate (gm/sec)	Dialution (%)
	Vibration amplitude (µm)	Vibration Frequency (Hz)	Welding speed (mm/sec)	Electrode Angle (°)				
1	15.0	100.0	2.0	15.0				
2	25.0	100.0	2.0	15.0				
3	15.0	200.0	2.0	15.0				
4	25.0	200.0	2.0	15.0				
5	15.0	100.0	5.0	15.0				
6	25.0	100.0	5.0	15.0				
7	15.0	200.0	5.0	15.0				
8	25.0	200.0	5.0	15.0				
9	15.0	100.0	2.0	30.0				
10	25.0	100.0	2.0	30.0				
11	15.0	200.0	2.0	30.0				
12	25.0	200.0	2.0	30.0				
13	15.0	100.0	5.0	30.0				
14	25.0	100.0	5.0	30.0				
15	15.0	200.0	5.0	30.0				
16	25.0	200.0	5.0	30.0				
17	12.9	150.0	3.5	22.5				
18	27.1	150.0	3.5	22.5				
19	20.0	79.29	3.5	22.5				
20	20.0	220.7	3.5	22.5				
21	20.0	150.0	1.4	22.5				
22	20.0	150.0	5.6	22.5				
23	20.0	150.0	3.5	11.9				
24	20.0	150.0	3.5	33.1				
25	20.0	150.0	3.5	22.5				
26	20.0	150.0	3.5	22.5				
27	20.0	150.0	3.5	22.5				
28	20.0	150.0	3.5	22.5				
29	20.0	150.0	3.5	22.5				
30	20.0	150.0	3.5	22.5				

Table 3.3 shows the input parameters, those are free of vibration amplitude and frequency. Here, different welding speeds and electrode angles are used to find out the same output parameters and see the difference.

Table 3.3 : Total number of tests for the experiment without oscillation

No. Of Study	Input parameters				Output parameters (Experimental)			
	V_A Vibration amplitude (μm)	**V_F** Vibration Frequency (Hz)	**W_S** Welding speed (mm/sec)	**E_A** Electrode Angle (°)	Hardness (HRC)	Bending Strength (MPa)	Deposition rate (gm/sec)	Dialution (%)
1	0	0	1.4	15.0				
2	0	0	2	15.0				
3	0	0	3.5	15.0				
4	0	0	5	15.0				
5	0	0	5.6	15.0				
6	0	0	2	11.9				
7	0	0	2	15.0				
8	0	0	2	22.5				
9	0	0	2	30.0				
10	0	0	2	33.1				

3.4.3 Output parameters

There is a common goal of every experiments and that is outcome. If the outcome of any experiment is not good then the entire experiment is invalid. Therefore, output parameters of any experiments should be chosen carefully because the success depends on that. So, to make this experiment fruitful, output parameters are selected carefully so that input parameters have significant effect on the results. In this experiment, the selected output parameters are given below:

- Hardness
- Bending strength
- Deposition rate
- Dilution

Experimental results are fruitful or not, it cannot be decided if it is not checked properly. In this case, generally, welding process is done normally that means without oscillation. So, two types of data should be collected to compare with each other. That is why 30 tests are done with oscillation and 10 tests are done without oscillation.

3.4.4 Algorithm of the automatic process

In order to run the welding process automatically, here electrical relay circuit and software are used. Three types of switch connection are here:

- To control the vibration frequency
- To control start and end of the welding operations
- Controlling axis movement of the welding holder

Switch 1 controls the frequency, which is given to the job piece during welding operation. In this case, ***Switch 1*** is connected to an electrical circuit. This electrical circuit has a cable port through that it can be connected with a computer. By using a code in "Arduino", frequency can be changed, when it is necessary.

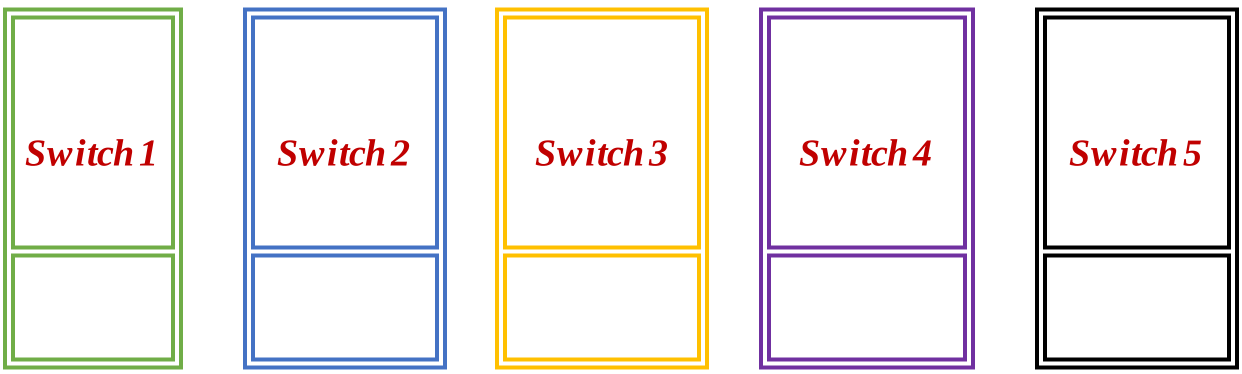


Figure 3.4.j : Different Switches of automatic control

Figure 3.12 shows different switches of the automatic control of welding operation. Here ***Switch 2*** controls the Y-axis movement of welding holder. When the welding operation starts, first ***Switch 2*** is pressed. As ***Switch 2*** controls the vertical Y-axis, it moves the holder downward from its original position and takes the welding filler rod to the job piece. The filler rod gives one touch to the job piece to make sure electricity is passing properly and stops keeping 1mm gap between the tip point of the filler rod and job piece. After that, ***Switch 3*** is pressed and current begins to pass through the filler rod tip and welding starts. Then ***Switch 4*** is pressed and according to the given welding speed, filler rod starts to move forward horizontally to the X-axis. When the welding operation is complete, ***Switch 5*** is pressed. ***Switch 5*** gives the command to the welding holder to stop welding and return to its original position according to coding of the software and it does. This is how one welding operation becomes complete and ready for the next operation.

3.5 Concluding remark:

Welding is a process of joining two metals but different welding processes have different strength quality. This quality of strength depends on many parameters like dilution rate, deposition rate, welding angle, welding speed etc. It has been found through literature study that welding with oscillation has a great effect on joining section of two metals. First, a design is established based on the concept of the experiment and then it is analyzed for feasibility. According to the design, an experimental set up is established. Then several welding processes with oscillation have been conducted. After getting experimental specimens, output parameters – hardness, bending strength, deposition rate and dilution are calculated. Calculation results are plotted in a graphical representation to see the relation with input parameters and analyze the changes of mechanical properties of the joining section.

Chapter 4 Effect of the process parameters

4.1 Introduction

This chapter discusses about the effect of process parameters. In every experiment, there are two types of parameters- input and output parameter. This chapter will show that how the input parameters play significant role to change the output of the experiment. Design Expert 7.00 software is used to find out the model equation and percentage of error is also determined. The relation between input and output parameter is found out through graphical analysis.

4.2 Experiment results

After getting the experimental results with and without oscillation, it has become clear that there is a significant change in the mechanical properties of the joining point. These results are shown in the table 4.1 and 4.2 below:

Table 4.1 : Experimental Results using Vibration or oscillation

No. Of Study	Input parameters				Output parameters (Experimental)			
	V_A Vibration amplitude (µm)	**V_F** Vibration Frequency (Hz)	**W_S** Welding speed (mm/sec)	**E_A** Electrode Angle (°)	Hardness (HRC)	Bending Strength (MPa)	Deposition rate (gm/sec)	Dialution (%)
1	15.0	100.0	2.0	15.0	34.54	13.20	0.68	34.0
2	25.0	100.0	2.0	15.0	41.07	17.90	0.70	35.0
3	15.0	200.0	2.0	15.0	41.14	17.80	0.72	38.0
4	25.0	200.0	2.0	15.0	48.00	22.50	0.75	41.0
5	15.0	100.0	5.0	15.0	29.19	8.60	0.48	26.0
6	25.0	100.0	5.0	15.0	34.67	13.50	0.50	23.0
7	15.0	200.0	5.0	15.0	34.40	13.20	0.53	30.0
8	25.0	200.0	5.0	15.0	41.20	17.90	0.55	31.0
9	15.0	100.0	2.0	30.0	27.21	8.60	0.59	22.0
10	25.0	100.0	2.0	30.0	35.33	13.20	0.61	21.0
11	15.0	200.0	2.0	30.0	34.27	13.40	0.63	32.0
12	25.0	200.0	2.0	30.0	41.07	18.00	0.66	29.0
13	15.0	100.0	5.0	30.0	22.13	4.00	0.42	10.0
14	25.0	100.0	5.0	30.0	29.19	8.80	0.44	14.0
15	15.0	200.0	5.0	30.0	28.60	8.60	0.47	22.0
16	25.0	200.0	5.0	30.0	34.40	13.00	0.50	23.0
17	12.9	150.0	3.5	22.5	28.40	8.60	0.57	19.0
18	27.1	150.0	3.5	22.5	34.40	13.30	0.60	21.0
19	20.0	79.29	3.5	22.5	29.19	8.60	0.62	23.0
20	20.0	220.7	3.5	22.5	34.67	17.80	0.65	39.0
21	20.0	150.0	1.4	22.5	34.40	17.50	0.33	42.0
22	20.0	150.0	5.6	22.5	28.79	8.60	0.49	17.0
23	20.0	150.0	3.5	11.9	34.27	13.40	0.57	32.0
24	20.0	150.0	3.5	33.1	29.19	8.60	0.58	23.0
25	20.0	150.0	3.5	22.5	34.80	13.20	0.40	29.0
26	20.0	150.0	3.5	22.5	34.90	13.10	0.39	30.0
27	20.0	150.0	3.5	22.5	34.70	13.30	0.41	31.0
28	20.0	150.0	3.5	22.5	34.60	13.00	0.39	30.0
29	20.0	150.0	3.5	22.5	35.00	13.40	0.40	31.0
30	20.0	150.0	3.5	22.5	34.80	13.20	0.41	29.0

Table 4.2 : Experimental Results for Without Vibration or oscillation

No. Of Study	Input parameters				Output parameters (Experimental)			
	V_A Vibration amplitude (μm)	V_F Vibration Frequency (Hz)	W_S Welding speed (mm/sec)	E_A Electrode Angle (°)	Hardness (HRC)	Bending Strength (MPa)	Deposition rate (gm/sec)	Dialution (%)
31	0	0	1.4	15.0	34.0	15.0	0.50	26.0
32	0	0	2	15.0	33.0	14.0	0.48	24.0
33	0	0	3.5	15.0	30.0	12.0	0.45	21.0
34	0	0	5	15.0	28.0	10.0	0.41	19.0
35	0	0	5.6	15.0	27.0	9.0	0.38	18.0
36	0	0	2	11.9	34.5	16.0	0.50	25.0
37	0	0	2	15.0	33.0	14.0	0.48	24.0
38	0	0	2	22.5	31.0	11.0	0.45	22.0
39	0	0	2	30.0	29.0	9.0	0.47	20.0
40	0	0	2	33.1	28.0	8.0	0.48	19.0

4.3 Model equation and ANOVA output

Using Design Expert 7.00 software, model equation and ANOVA output is found for every output parameters-Hardness, Bending strength, Deposition rate, Dilution.

4.3.1 ANOVA for Hardness:

Fit summery for hardness is shown in Table 4.3:

Table 4.3 : Fit summery table for Hardness

Sequential Model Sum of Squares [Type I]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	370.38	1	370.38			
Linear vs Mean	0.62	4	0.15	57.90	< 0.0001	Suggested
2FI vs Linear	7.078E-003	6	1.180E-003	0.38	0.8843	
Quadratic vs 2FI	5.762E-004	4	1.441E-004	0.037	0.9971	
Cubic vs Quadra	0.015	8	1.889E-003	0.30	0.9421	Aliased
Residual	0.044	7	6.243E-003			
Total	371.06	30	12.37			

Systematic analysis of variance for hardness is given in Table 4.4:

Table 4.4 : Analysis of variance table for Hardness

Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.62	4	0.15	57.90	< 0.0001	significant
A-Vib_Amp	*0.17*	*1*	*0.17*	*64.72*	*< 0.0001*	
B-Vib_Fre	*0.15*	*1*	*0.15*	*55.19*	*< 0.0001*	
C-Wel_Spd	*0.14*	*1*	*0.14*	*52.86*	*< 0.0001*	
D-Angle	*0.16*	*1*	*0.16*	*58.83*	*< 0.0001*	
Residual	0.066	25	2.659E-003			
Lack of Fit	*0.066*	*20*	*3.323E-003*			
Pure Error	*0.000*	*5*	*0.000*			
Cor Total	0.68	29				

From Table 4.4, the following point can be found:

- The Model F-value of 57.90 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant.
- In this case A, B, C, D are significant model terms.
- Values greater than 0.1000 indicate the model terms are not significant.
- If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

4.3.2 Model Equation:

$$\ln(Hardness) = 3.34656 + 0.018552 \times V_A + 1.71317 \times 10^{-3} \times V_F - 0.055885 \times W_D - 0.011791 \times E_A \tag{4.1}$$

Here,

V_A = Vibration Amplitude (μm); V_F = Vibration Frequency (Hz)

W_D = Welding Speed (mm/sec); E_A = Electrode Angle (°)

4.3.3 ANOVA for Bending Strength:

Fit summery for bending strength is shown in Table 4.5:

Table 4.5 : Fit summery table for Bending strength

Sequential Model Sum of Squares [Type I]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	188.43	1	188.43			
Linear vs Mean	3.21	4	0.80	61.14	< 0.0001	
2FI vs Linear	0.17	6	0.028	3.33	0.0205	Suggested
Quadratic vs 2FI	0.046	4	0.012	1.54	0.2423	
Cubic vs Quadra	0.052	8	6.527E-003	0.75	0.6561	Aliased
Residual	0.061	7	8.733E-003			
Total	191.96	30	6.40			

Systematic analysis of variance for bending strength is given in Table 4.6:

Table 4.6 : Analysis of variance table for Bending strength

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.38	10	0.34	40.16	< 0.0001	significant
A-Vib_Amp	*0.74*	*1*	*0.74*	*87.51*	*< 0.0001*	
B-Vib_Fre	*0.87*	*1*	*0.87*	*103.72*	*< 0.0001*	
C-Wel_Spd	*0.87*	*1*	*0.87*	*104.04*	*< 0.0001*	
D-Angle	*0.73*	*1*	*0.73*	*86.28*	*< 0.0001*	
AB	*0.033*	*1*	*0.033*	*3.91*	*0.0627*	
AC	*0.030*	*1*	*0.030*	*3.59*	*0.0736*	
AD	*0.025*	*1*	*0.025*	*2.96*	*0.1017*	
BC	*0.021*	*1*	*0.021*	*2.54*	*0.1273*	
BD	*0.028*	*1*	*0.028*	*3.35*	*0.0831*	
CD	*0.031*	*1*	*0.031*	*3.66*	*0.0710*	
Residual	0.16	19	8.408E-003			
Lack of Fit	*0.16*	*14*	*0.011*			
Pure Error	*0.000*	*5*	*0.000*			
Cor Total	3.54	29				

From Table 4.6, the following point can be found:

- The Model F-value of 40.16 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant.
- In this case A, B, C, D are significant model terms.
- Values greater than 0.1000 indicate the model terms are not significant.
- If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

4.3.4 Model Equation:

$$\begin{aligned}\ln(\textit{Bending Strength}) = {} & 2.83267 + 0.021641 \times V_A + 3.58006 \times 10^{-3} \times V_F - 0.24062 \times W_D - 0.049555 \times E_A \\ & - 1.81305 \times 10^{-4} \times V_A V_F + 5.78903 \times 10^{-3} \times V_A W_D + 1.05134 \times 10^{-3} \times V_A E_A \\ & + 4.87406 \times 10^{-4} \times V_F W_D + 1.11842 \times 10^{-4} \times V_F E_A - 3.89770 \times 10^{-3} \times W_D E_A\end{aligned} \tag{4.2}$$

Here,

V_A = Vibration Amplitude (μm); V_F = Vibration Frequency (Hz)

W_D = Welding Speed (mm/sec); E_A = Electrode Angle (°)

4.3.5 ANOVA for Deposition Rate:

Fit summery for deposition rate is shown in Table 4.7:

Table 4.7 : Fit summery table for Deposition rate

Sequential Model Sum of Squares [Type I]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	12.82	1	12.82			Suggested
Linear vs Mean	0.28	4	0.071	1.49	0.2342	
2FI vs Linear	2.469E-003	6	4.115E-004	6.608E-003	1.0000	
Quadratic vs 2FI	0.77	4	0.19	7.06	0.0021	Suggested
Cubic vs Quadra	0.30	8	0.038	2.47	0.1255	Aliased
Residual	0.11	7	0.015			
Total	14.29	30	0.48			

From Table 4.8, the following point can be found:

- The Model F-value of 2.76 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant.
- In this case A, B, C, D are significant model terms.
- Values greater than 0.1000 indicate the model terms are not significant.
- If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Systematic analysis of variance for hardness is given in Table 4.8:

Table 4.8 : Analysis of variance table for Deposition rate

Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.06	14	0.076	2.76	0.0301	significant
A-Vib_Amp	*8.342E-003*	*1*	*8.342E-003*	*0.30*	*0.5890*	
B-Vib_Fre	*0.030*	*1*	*0.030*	*1.09*	*0.3132*	
C-Wel_Spd	*0.20*	*1*	*0.20*	*7.16*	*0.0173*	
D-Angle	*0.049*	*1*	*0.049*	*1.80*	*0.1994*	
AB	*8.369E-005*	*1*	*8.369E-005*	*3.058E-003*	*0.9566*	
AC	*8.369E-005*	*1*	*8.369E-005*	*3.058E-003*	*0.9566*	
AD	*1.029E-004*	*1*	*1.029E-004*	*3.761E-003*	*0.9519*	
BC	*1.685E-003*	*1*	*1.685E-003*	*0.062*	*0.8074*	
BD	*2.571E-004*	*1*	*2.571E-004*	*9.394E-003*	*0.9241*	
CD	*2.571E-004*	*1*	*2.571E-004*	*9.394E-003*	*0.9241*	
A^2	*0.14*	*1*	*0.14*	*5.13*	*0.0388*	
B^2	*0.25*	*1*	*0.25*	*9.13*	*0.0086*	
C^2	*0.039*	*1*	*0.039*	*1.43*	*0.2510*	
D^2	*0.12*	*1*	*0.12*	*4.44*	*0.0523*	
Residual	0.41	15	0.027			
Lack of Fit	*0.41*	*10*	*0.041*			
Pure Error	*0.000*	*5*	*0.000*			
Cor Total	1.47	29				

4.3.6 Model Equation:

$$\begin{aligned}\ln(\mathit{Depsition\ Rate}) = {} & 3.62962 - 0.19605\times V_A - 0.019767\times V_F + 0.10054\times W_D - 0.10213\times E_A \\ & + 9.14818\times10^{-6}\times V_A V_F + 3.04939\times10^{-4}\times V_A W_D + 6.76318\times10^{-5}\times V_A E_A \\ & + 1.36819\times10^{-4}\times V_F W_D + 1.06895\times10^{-5}\times V_F E_A + 3.56317\times10^{-4}\times W_D E_A \\ & + 4.90434\times10^{-3}\times V_A{}^2 + 6.54561\times10^{-5}\times V_F{}^2 - 0.028737\times W_D{}^2 + 2.02903\times10^{-3}\times E_A{}^2\end{aligned} \tag{4.3}$$

Here,

V_A = Vibration Amplitude (μm); V_F = Vibration Frequency (Hz)

W_D = Welding Speed (mm/sec); E_A = Electrode Angle (°)

4.3.7 ANOVA for Dilution:

Fit summery for dilution is shown in Table 4.9:

Table 4.9 : Fit summery table for Dilution

Sequential Model Sum of Squares [Type I]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	321.22	1	321.22			
Linear vs Mean	2.31	4	0.58	22.55	< 0.0001	Suggested
2FI vs Linear	0.17	6	0.028	1.15	0.3744	
Quadratic vs 2FI	0.28	4	0.069	5.39	0.0068	Suggested
Cubic vs Quadra	0.16	8	0.019	3.59	0.0547	Aliased
Residual	0.038	7	5.409E-003			
Total	324.17	30	10.81			

From Table 4.10, the following point can be found:

- The Model F-value of 15.31 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant.
- In this case A, B, C, D are significant model terms.
- Values greater than 0.1000 indicate the model terms are not significant.
- If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

4.3.8 Model Equation:

$$\begin{aligned}\ln(Dilution) = {} & 2.55566 + 0.24876 \times V_A - 7.82848\times10^{-3} \times V_F - 0.17037 \times W_D - 0.047886 \times E_A \\ & - 3.53875\times10^{-5} \times V_A V_F + 2.75915\times10^{-3} \times V_A W_D + 3.68005\times10^{-4} \times V_A E_A \\ & + 6.32976\times10^{-4} \times V_F W_D + 2.11886\times10^{-4} \times V_F E_A - 3.31292\times10^{-3} \times W_D E_A \\ & - 6.43646\times10^{-3} \times V_A^2 + 1.66453\times10^{-5} \times V_F^2 - 6.85794\times10^{-3} \times W_D^2 - 1.39441\times10^{-4} \times E_A^2\end{aligned} \quad (4.4)$$

Here,

V_A = Vibration Amplitude(μm); V_F = Vibration Frequency(Hz)

W_D = Welding Speed(mm/sec); E_A = Electrode Angle$(°)$

Systematic analysis of variance for dilution is given in Table 4.10:

Table 4.10 : Analysis of variance for Dilution

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2.76	14	0.20	15.31	< 0.0001	significant
A-Vib_Amp	*7.709E-003*	*1*	*7.709E-003*	*0.60*	*0.4512*	
B-Vib_Fre	*0.59*	*1*	*0.59*	*45.94*	*< 0.0001*	
C-Wel_Spd	*0.92*	*1*	*0.92*	*71.22*	*< 0.0001*	
D-Angle	*0.80*	*1*	*0.80*	*61.85*	*< 0.0001*	
AB	*1.252E-003*	*1*	*1.252E-003*	*0.097*	*0.7595*	
AC	*6.852E-003*	*1*	*6.852E-003*	*0.53*	*0.4770*	
AD	*3.047E-003*	*1*	*3.047E-003*	*0.24*	*0.6337*	
BC	*0.036*	*1*	*0.036*	*2.80*	*0.1150*	
BD	*0.10*	*1*	*0.10*	*7.84*	*0.0134*	
CD	*0.022*	*1*	*0.022*	*1.73*	*0.2087*	
A^2	*0.24*	*1*	*0.24*	*18.76*	*0.0006*	
B^2	*0.016*	*1*	*0.016*	*1.25*	*0.2803*	
C^2	*2.222E-003*	*1*	*2.222E-003*	*0.17*	*0.6838*	
D^2	*5.742E-004*	*1*	*5.742E-004*	*0.045*	*0.8356*	
Residual	0.19	15	0.013			
Lack of Fit	*0.19*	*10*	*0.019*			
Pure Error	*0.000*	*5*	*0.000*			
Cor Total	2.95	29				

4.4 Output parameters with model equation and % Error:

After determining the model equations 4.1, 4.2, 4.3 & 4.4, following Table 4.11 has been generated. Table 4.11 shows percentage of error of the output parameter.

Table 4.11 Output parameters with model equation and % Error

No. Of Study	Output parameters (Empirical)				% Error			
	Hardness (HRC)	Bending Strength (MPa)	Deposition rate (gm/sec)	Dialution (%)	Hardness (HRC)	Bending Strength (MPa)	Deposition rate (gm/sec)	Dialution (%)
1	33.37	13.16	0.65	35.2	3.4	0.3	4.0	3.6
2	40.17	17.92	0.67	34.8	2.2	0.1	4.3	0.5
3	39.60	18.70	0.68	39.3	3.7	5.1	5.3	3.3
4	47.67	21.24	0.71	37.4	0.7	5.6	5.8	8.7
5	28.22	8.06	0.52	21.6	3.3	6.3	7.9	17.0
6	33.97	13.05	0.54	23.2	2.0	3.3	7.4	0.7
7	33.49	13.25	0.56	29.1	2.7	0.4	6.4	3.1
8	40.31	17.91	0.59	30.1	2.2	0.0	7.2	2.8
9	27.96	8.34	0.58	21.1	2.7	3.0	1.9	3.9
10	33.66	13.30	0.60	22.1	4.7	0.7	1.6	5.1
11	33.18	14.02	0.61	32.4	3.2	4.6	2.5	1.1
12	39.94	18.64	0.64	32.6	2.7	3.6	2.5	12.4
13	23.64	4.29	0.47	11.2	6.8	7.2	11.1	11.5
14	28.46	8.13	0.49	12.7	2.5	7.6	11.0	9.6
15	28.06	8.34	0.52	20.6	1.9	3.1	9.8	6.2
16	33.78	13.19	0.55	22.6	1.8	1.5	9.1	1.7
17	29.44	9.35	0.52	20.4	3.7	8.7	9.4	7.6
18	38.28	16.08	0.55	21.6	11.3	20.9	8.9	2.9
19	29.74	9.12	0.55	24.7	1.9	6.1	11.9	7.4
20	37.90	16.47	0.61	40.2	9.3	7.5	6.3	3.1
21	37.80	16.48	0.42	38.1	9.9	5.8	27.3	9.4
22	29.82	9.12	0.32	20.8	3.6	6.0	35.2	22.2
23	38.04	16.05	0.56	37.9	11.0	19.8	1.7	18.3
24	29.62	9.36	0.49	21.5	1.5	8.9	16.0	6.4
25	33.57	12.26	0.42	29.0	3.5	7.1	3.9	0.0
26	33.57	12.26	0.42	29.0	3.8	6.4	6.6	3.3
27	33.57	12.26	0.42	29.0	3.3	7.8	1.4	6.5
28	33.57	12.26	0.42	29.0	3.0	5.7	6.6	3.3
29	33.57	12.26	0.42	29.0	4.1	8.5	3.9	6.5
30	33.57	12.26	0.42	29.0	3.5	7.1	1.4	0.0

4.5 Study of effect

Input parameters- Vibration amplitude, Vibration frequency, Welding speed and Electrode angle have vital effect on output parameters- Hardness, Bending strength, Deposition rate and Dilution.

Generating the model equation, graphical representation has been done to analyze the effect of input parameters on output.

4.5.1 Effect of Vibration Amplitude

One of the input parameters is amplitude. Changing the amplitude of the oscillation causes a significant variation of the mechanical properties of the output parameters, which is shown in Figure 4.1

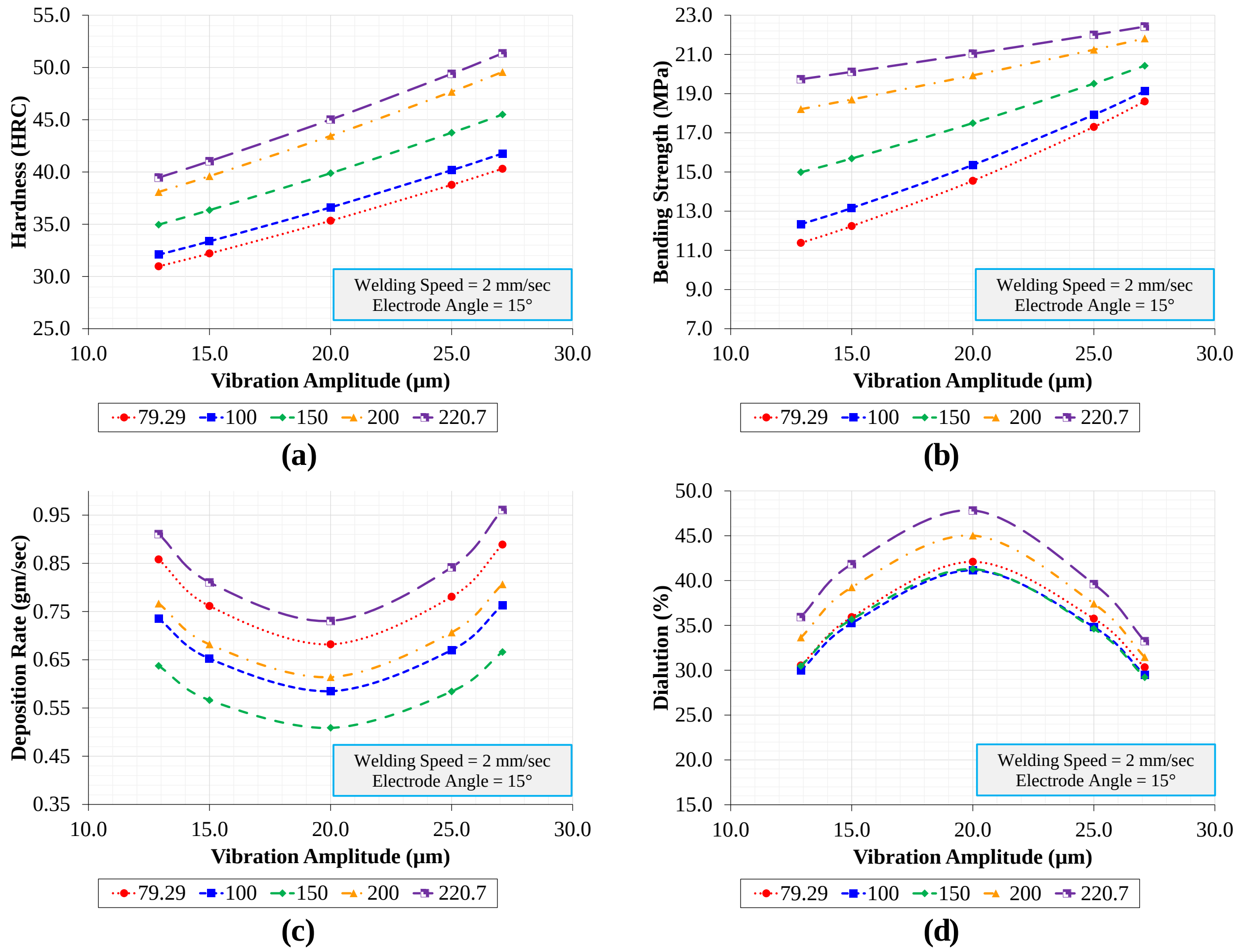
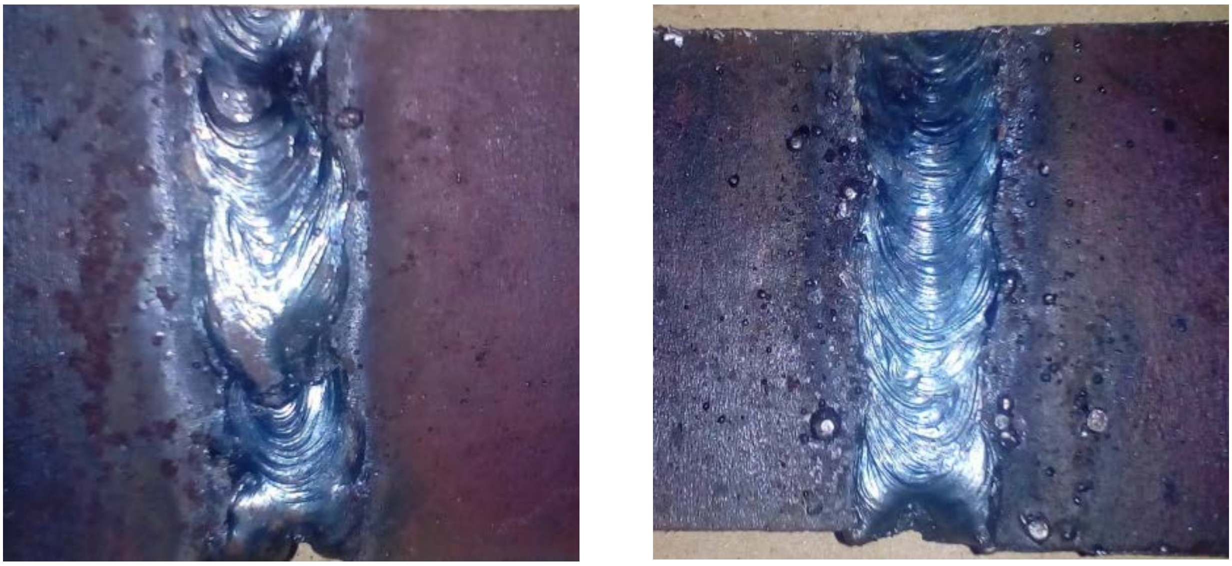


Figure 4.5.a: Effect of vibration amplitude for different vibration frequency on (a) Hardness (b) Bending strength (c) Deposition Rate (d) Dilution.

In Figure 4.1 (a), it can be seen that with the increase of vibration amplitude, hardness increases. The reason of this phenomena is that, amplitude gives the job piece perfect movement range so that the job piece can oscillate smoothly which makes remaining bubble in the welded joint out of the joint. This is why porosity decreases in the joint. Figure 4.2 (a) indicates the welded joint is irregular and porous when vibration amplitude has been kept low. Figure 4.2 (b) shows when the amplitude has been increased then welded joint is in regular shape and less porous.



V_A =15.0µm, V_F =100 Hz,
W_S = 2 mm/sec, E_A=15^0 (Sample No. 1)
(a)

V_A =25µm, V_F =200 Hz,
W_S = 2.0mm/sec, E_A=15^0 (Sample No. 4)
(b)

Figure 4.5.b : Porosity in welded joint with the change of vibration amplitude (a) more porous (b) less porosity.

Figure 4.1 (b) shows bending strength curves are increasing with the increment of amplitude with different frequency. The increase of amplitude provides more penetration to the joining point because it helps the molten metal to enter into the lower depth of the joint. In Figure 4.1 (b), Bending strength varies with penetration quality. If penetration is high then bending strength is high and if it is low then so as bending strength. Figure 4.3 (a) shows lower amplitude and frequency provides less penetration where in Figure 4.3 (b), high amplitude with high frequency provide almost complete penetration and stronger joint.

V_A =15µm, V_F =100 Hz, W_S = 2.0mm/sec, E_A=30^0 (Sample No. 9)

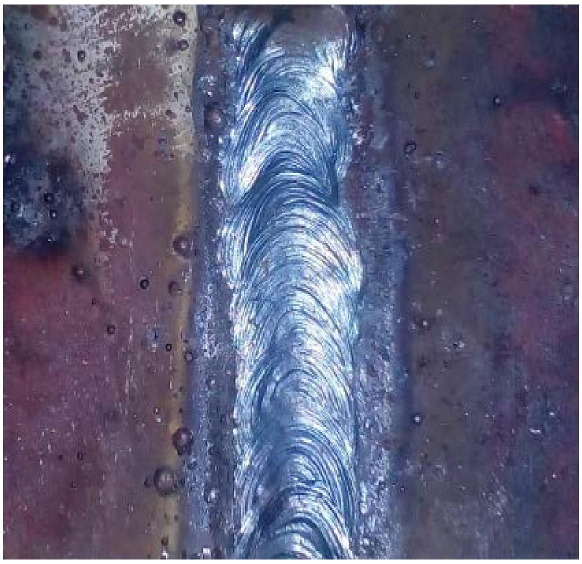
(a)

V_A =25µm, V_F =175 Hz, W_S = 2.0mm/sec, E_A=30^0 (Sample No. 12)

(b)

Figure 4.5.c : Higher penetration with the change of amplitude in welding (a) less penetration (b) complete penetration.

Figure 4.1 (c) shows that, deposition rate is decreasing with the increment of amplitude but after a certain period, the curve is going up. Because it is clear that, deposition rate starts to grow after a certain period. Figure 4.4 (b) shows the deposition rate gets lower in low amplitude with low frequency but in Figure 4.4 (a), it gets higher in high amplitude with frequency.



V_A =20µm, V_F =220.7 Hz,
W_S = 3.5mm/sec, E_A=22.5^0 (Sample No.20)
(a)

V_A =15.0µm, V_F =100 Hz,
W_S = 2 mm/sec, E_A=15^0 (Sample No. 1)
(b)

Figure 4.5.d : Change of deposition rate with amplitude variation (a) high deposition rate (b) low deposition rate.

V_A =15µm, V_F =100 Hz, W_S = 5.0mm/sec, E_A=30^0 (Sample No.13)
(a)

V_A =20µm, V_F =150 Hz, W_S = 1.4mm/sec, E_A=22.5^0 (Sample No.21)
(b)

Figure 4.5.e : Change of dilution with the variation of vibration amplitude (a) less dilution (b) more dilution.

Figure 4.1 (d) shows that at first dilution increases but after a certain point, it goes down but it can be easily said that within 20-25µm amplitude with high frequency it provides better result. Figure 4.5 (a) shows low amplitude gives lower dilution percentage but Figure 4.5 (b) indicates with high frequency high amplitude provides higher dilution percentage.

4.5.2 Effect of Vibration Frequency

Frequency plays a vital role of changing the mechanical properties of the joining point is shown in Figure 4.6 below:

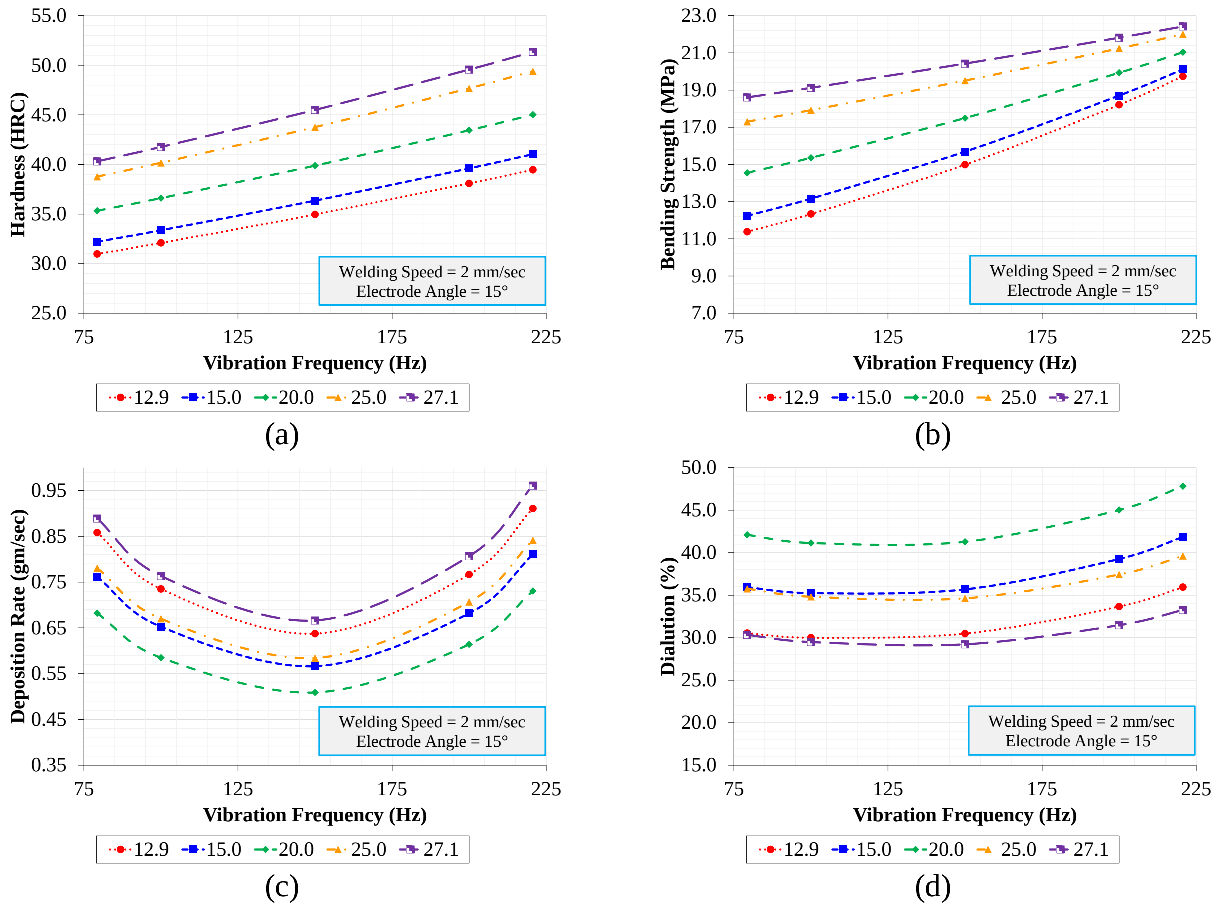


Figure 4.5.f : Effect of vibration frequency for different vibration amplitude on (a) Hardness (b) Bending strength (c) Deposition Rate (d) Dilution

Figure 4.6 (a) shows hardness of the joining point is improving with the increase of frequency. Frequency helps the joining point to release its bubble from the molten metal. In Figure 4.7 (a), if low frequency is provided with low amplitude then high amount of porous welded joint is seen with irregular shape but in Figure 4.7 (b), high frequency with high amplitude is given then it shows better result because now those bubbles are not there for oscillation.

V_A =15µm, V_F =100 Hz,
W_S = 5.0mm/sec, E_A=15^0 (Sample No.5)
(a)

V_A =25µm, V_F =200 Hz,
W_S = 5.0mm/sec, E_A=30^0 (Sample No.16)
(b)

Figure 4.5.g : Change of porosity in welding joint with the variation of frequency (a) high porosity (b) less porosity.

Figure 4.6 (b) also shows that frequency has a very significant role to improve the bending strength of the joining point. Here bending strength increases with frequency and amplitude. For getting more bending strength, it is necessary to increase the penetration of molten metal in joining point. Frequency helps to increase the penetration of molten metal. In Figure 4.8 (a), low frequency with less amplitude provides lower penetration than high frequency with high amplitude shown in Figure 4.8 (b).

V_A =15µm, V_F =100 Hz, W_S = 2.0mm/sec, E_A=15^0 (Sample No.1)

(a)

V_A =25µm, V_F =200 Hz, W_S = 2.0mm/sec, E_A=15^0 (Sample No.4)

(b)

Figure 4.5.h : Higher penetration in welding joint with the variation of frequency (a) low penetration (b) higher penetration.

V_A =25µm, V_F =200 Hz,
W_S = 5.0mm/sec, E_A=15^0 (Sample No.8)

(a)

V_A =25µm, V_F =100 Hz,
W_S = 2.0mm/sec, E_A=15^0 (Sample No.2)

(b)

Figure 4.5.i : High deposition rate with the variation of vibration frequency (a) high deposition rate (b) low deposition rate.

Figure 4.6 (c) represents deposition rate is decreasing first but after a certain point it is increasing with the increase of frequency and amplitude. In Figure 4.9 (a) high frequency with less amplitude gives higher deposition rate than low frequency with less amplitude shown in Figure 4.9 (b).

Figure 4.6 (d) also shows dilution of the joining point is also increasing with frequency and amplitude because having less porosity and more penetration, now molten metal can dilute more area of the job piece and create a strong bond. Dilution is lower with low frequency and amplitude shown in Figure 4.10 (a) but higher with high frequency and amplitude shown in Figure 4.10 (b).

V_A =15µm, V_F =100 Hz, W_S = 2.0mm/sec, E_A=15^0 (Sample No.1)

(a)

V_A =25µm, V_F =200 Hz, W_S = 2.0mm/sec, E_A=30^0 (Sample No.12)

(b)

Figure 4.5.j : Change of dilution with the variation of vibration frequency (a) low dilution percentage (b) high dilution percentage.

4.5.3 Effect of Welding Speed

Another input parameter is welding speed. After giving different welding speed, the change of the mechanical properties are given in Figure 4.11 & 4.12 below:

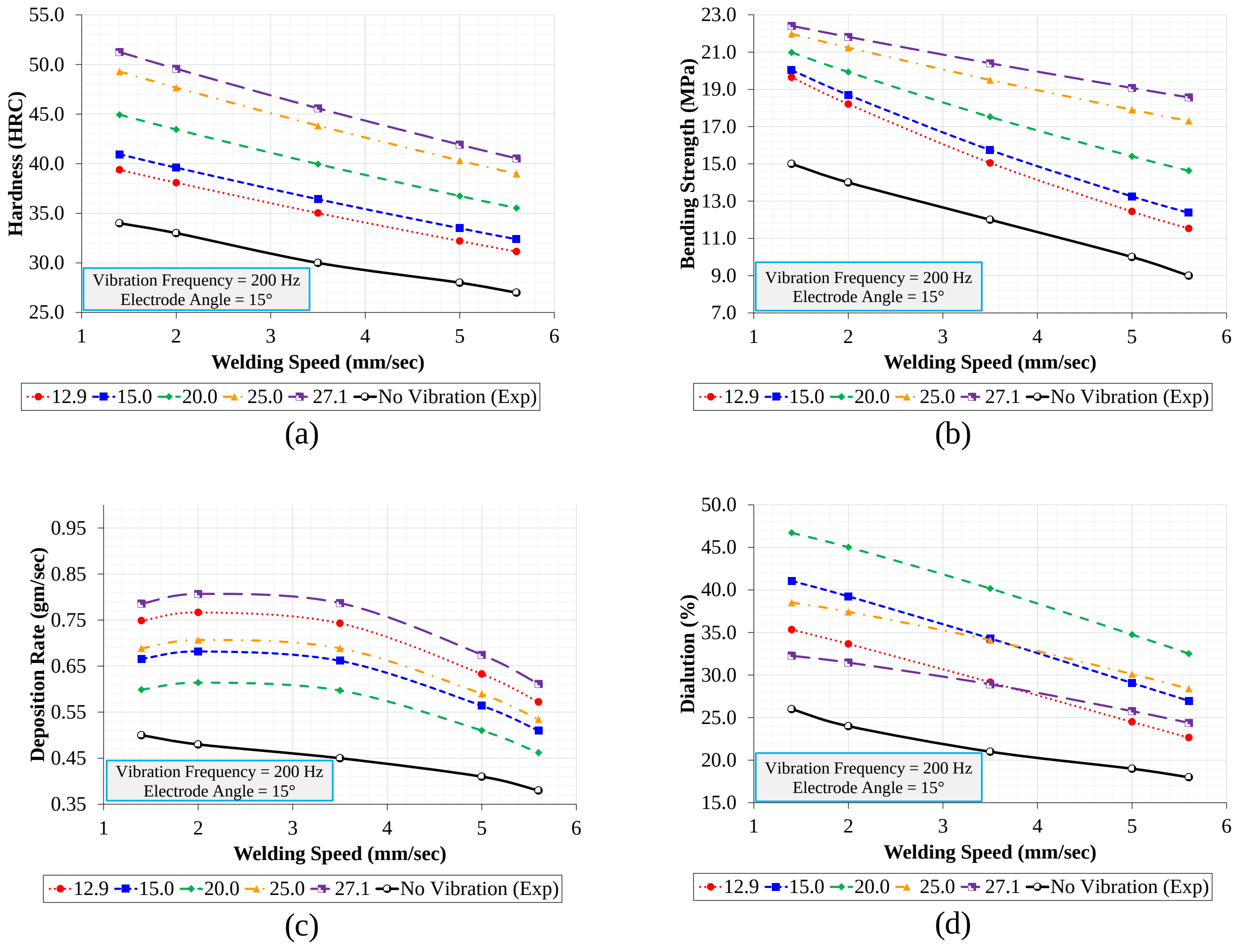
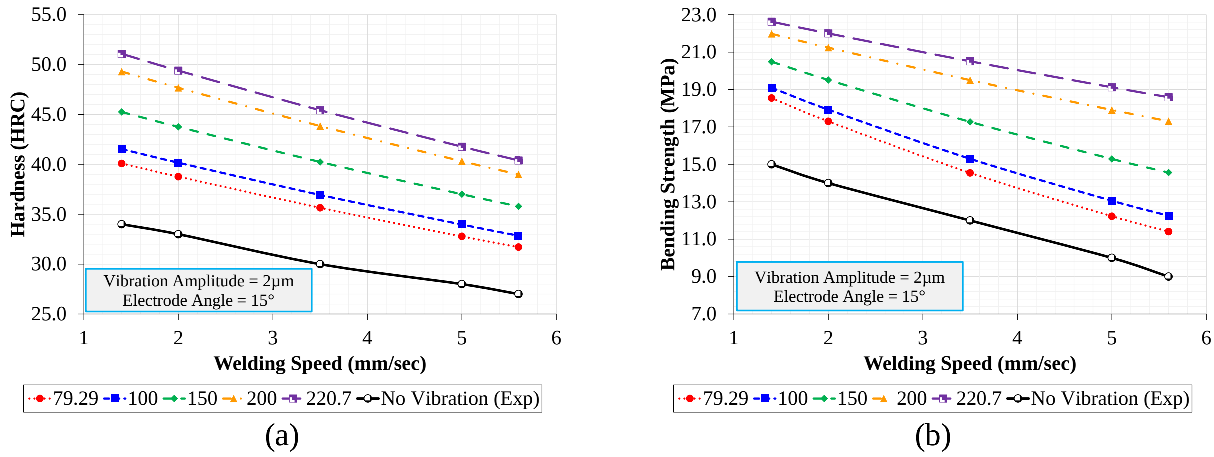
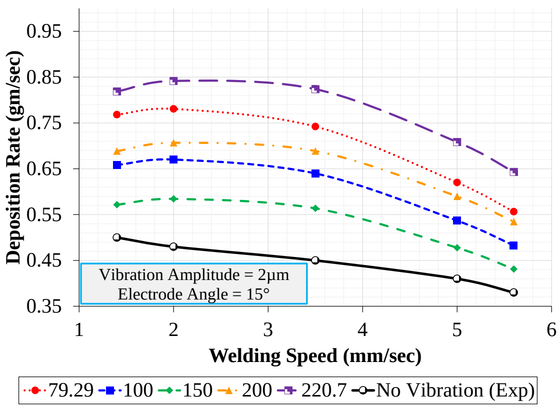
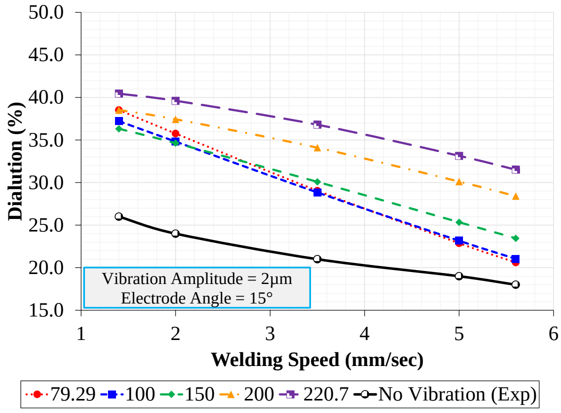


Figure 4.5.k : Effect of welding speed for different vibration frequency on (a) Hardness (b) Bending strength (c) Deposition Rate (d) Dilution





(c)

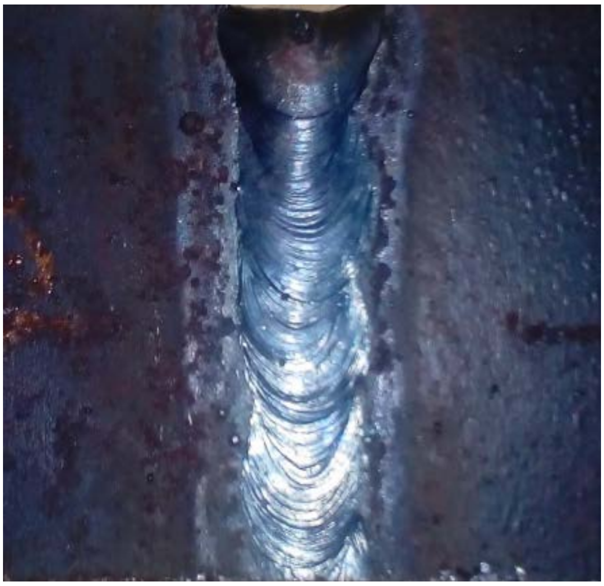


(d)

Figure 4.5.l : Effect of welding speed for different vibration amplitude (a) Hardness (b) Bending strength (c) Deposition Rate (d) dilution

Figure 4.11 (a) shows less welding speed is beneficial to the joining point because if welding speed is high then less amount of molten metal will enter into the joining point so obviously joining point will be weak. Here different colored lines of amplitude show how hardness is varying with the decrease of welding speed. Figure 4.12 (a) shows with different colored lines of frequency, how hardness is varying with the decrease of welding speed. In both Figure 4.11 (a) & Figure 4.12 (a), there is black line which represents non-oscillation line and it shows it is also decreasing with the increase of welding speed. Figure 4.13 (a) shows high welding speed produces welding joint with high amount of porosity. On the other hand, Figure 4.13 (b) less welding speed produces welding joint with less amount of porosity. Figure 4.13 (c) shows a welded joint with high porosity and irregular shape.

V_A =15µm, V_F =100 Hz,
W_S = 5mm/sec, E_A=30^0 (Sample No.13)
(a)



V_A =15µm, V_F =200Hz,
W_S = 2.0mm/sec, E_A=15^0 (Sample No.3)
(b)

V_A = 0, V_F = 0,
W_S = 2mm/sec, E_A=15^0 (Sample No.32)
(c)

Figure 4.5.m : Change of Porosity in welding joint with the variation welding speed (a) high porosity (b) less porosity. (c) Highly porous (no oscillation).

Figure 4.11 (b) shows different colored lines of amplitude is decreasing with the increase of welding speed because molten metal do not get enough time to penetrate the joint. Same, Figure 4.12 (b) represent that different colored lines of frequency is decreasing with the increase of welding speed. In both cases, black colored line shows the changing without oscillation. Figure 4.14 (a) shows incomplete penetration due to high welding speed. On the other hand, Figure 4.14 (b) shows complete penetration due to less welding speed. Figure 4.14 (c) shows no oscillation gives less penetration at the welding joint.

V_A =25µm, V_F =100 Hz, W_S = 5mm/sec, E_A=30^0 (Sample No.14)

(a)

V_A =15µm, V_F =200 Hz, W_S = 2.0mm/sec, E_A=30^0 (Sample No.11)

(b)

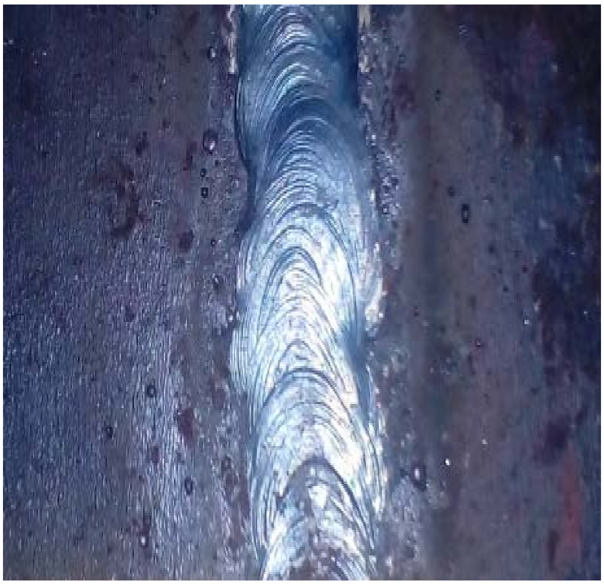
V_A = 0, V_F = 0, W_S = 5mm/sec, E_A=15^0 (Sample No.34)

(c)

Figure 4.5.n : Change of penetration with welding speed (a) less penetration (b) high penetration (c) less penetration (no oscillation).

Figure 4.11 (c) shows different colored lines of amplitude is decreasing with the increase of welding speed, that means deposition rate is decreasing and Figure 4.12 (c) shows that different colored lines of frequency is decreasing with the increase of welding speed, it also means deposition rate is going down. Figure 4.15 (a) shows high deposition rate due to less welding speed. On the other hand, Figure

4.15 (b) shows less deposition rate due to high welding speed. Figure 4.15 (c) represents irregular shape with less deposition rate when the welding speed is high (no oscillation).



V_A =15µm, V_F =200 Hz,
W_S = 2.0mm/sec, E_A=15^0 (Sample No.2)
(a)

V_A =20µm, V_F =150 Hz,
W_S = 5.6mm/sec, E_A=22.5^0 (Sample No.22)
(b)

V_A = 0, V_F = 0, W_S = 5.6mm/sec, E_A=15^0 (Sample No.35)
(c)

Figure 4.5.o : Variation of deposition rate with the change of welding speed (a) high deposition rate (b) less deposition rate (c) less deposition rate (no oscillation).

Figure 4.11 (d) & Figure 4.12 (d) shows less welding speed with high frequency and amplitude gives more dilution cause for higher penetration and less porosity in the joining point, more hot metal enters and it dilutes more area than without oscillation. Therefore, joining becomes stronger than normal welding process. Figure 4.16 (a) shows lower dilution because of higher welding speed, which is gradually turned into higher dilution with less welding speed shown in Figure 4.16 (b). In Figure 4.16 (c), it shows dilution percentage is very low when the welding process is without oscillation.

V_A =15μm, V_F =200 Hz, W_S = 5 mm/sec, E_A= 30^0 (Sample No. 15)

(a)

V_A =20μm, V_F =150 Hz, W_S = 1.4mm/sec, E_A=22.5^0 (Sample No.21)

(b)

V_A = 0, V_F = 0, W_S = 5.6mm/sec, E_A=15^0 (Sample No.35)

(c)

Figure 4.5.p : Change of dilution with the variation of welding speed (a) lower dilution (b) higher dilution (c) lower dilution (no oscillation).

4.5.4 Effect of Electrode Angle

Effect of electrode angle in this experiment is shown in Figure 4.17 & 4.18 below:

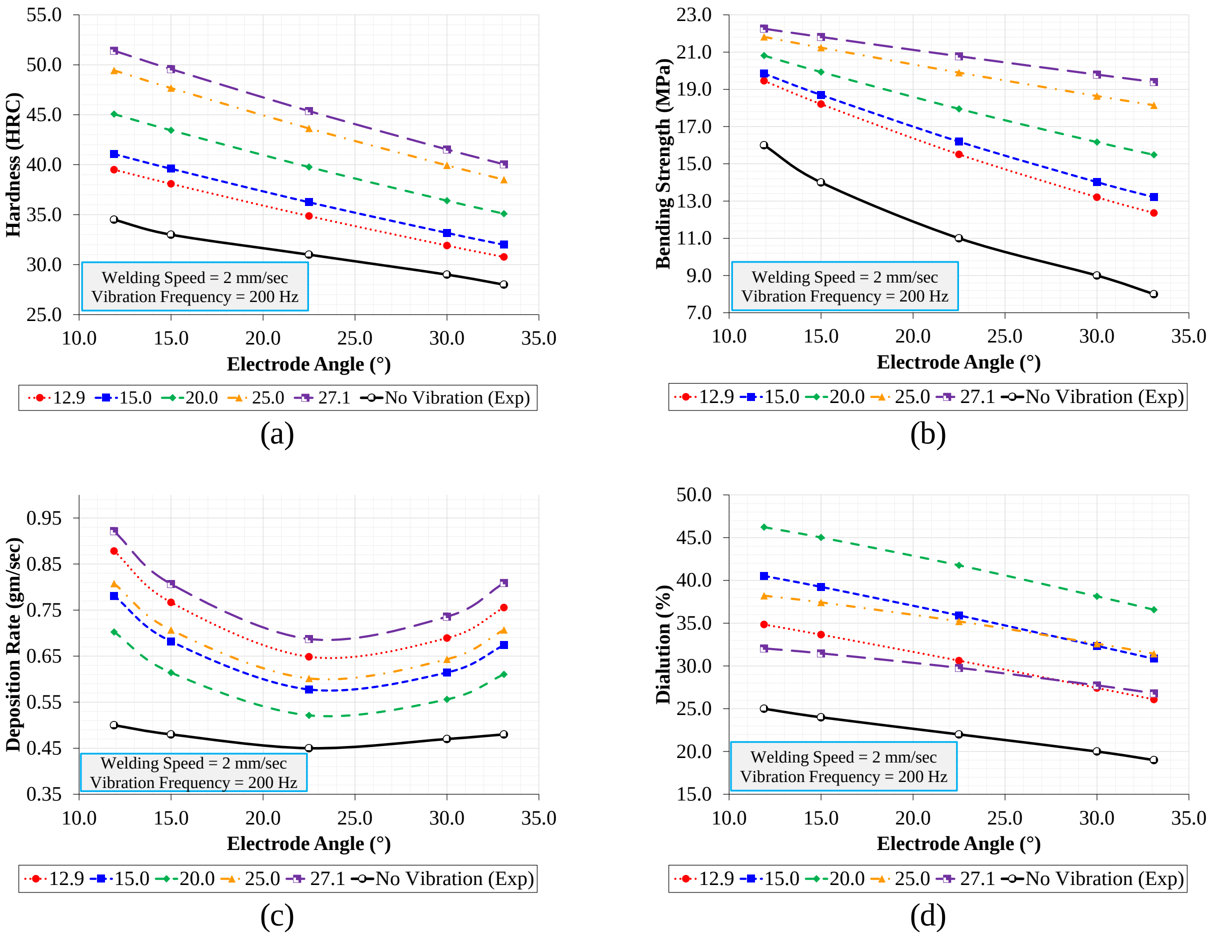
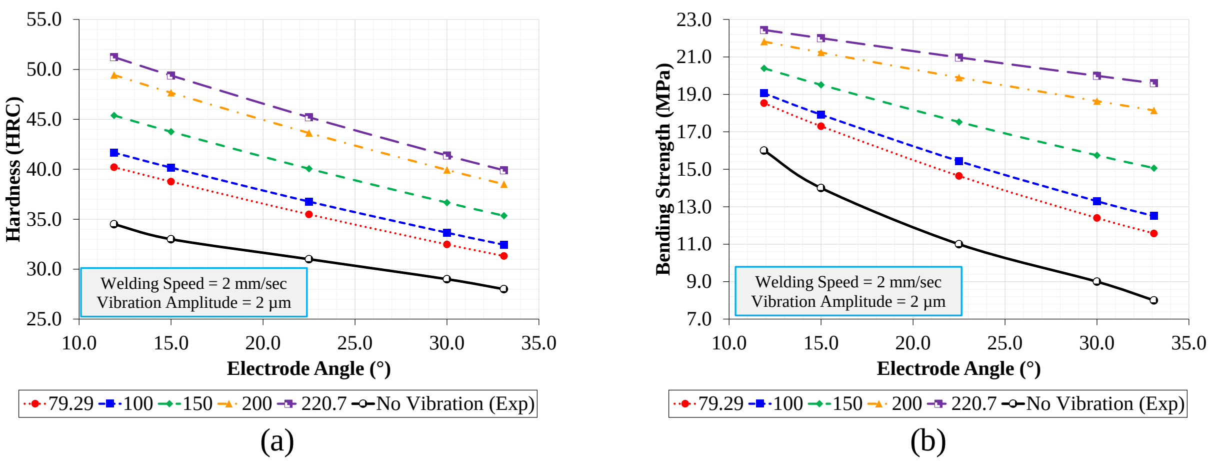


Figure 4.5.q : Effect of electrode angle for different vibration frequency on (a) Hardness (b) Bending strength (c) Deposition Rate (d) Dilution



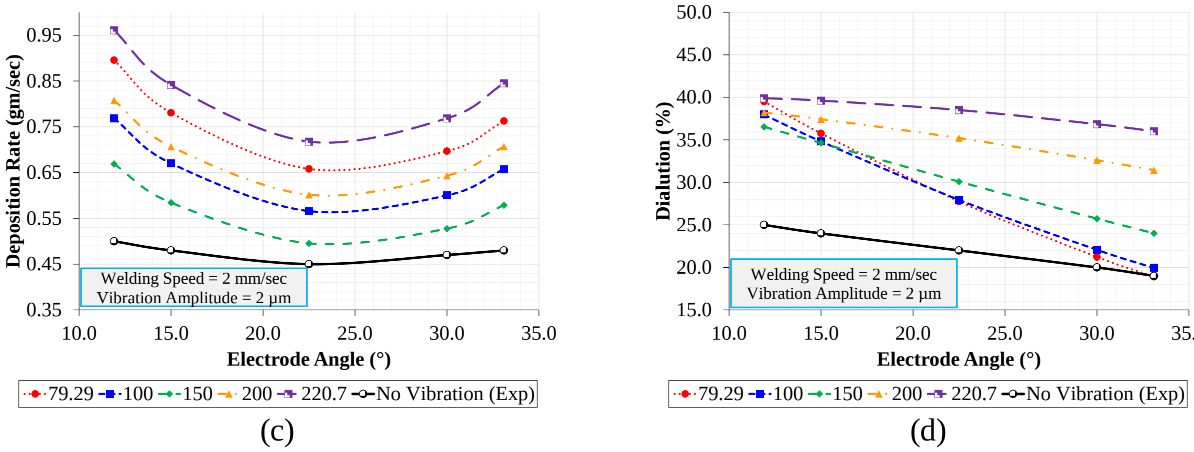


Figure 4.5.r : Effect of electrode angle for different vibration amplitude (a) Hardness (b) Bending strength (c) Deposition Rate (d) dilution

Figure 4.17 (a) & Figure 4.18 (a) show less electrode angle is good for the joining point because if electrode angle is high then molten metal will enter into the joining point in less amount so joining point will be weak. With high frequency, high amplitude, less welding speed and less electrode angle, molten metal will enter more into the joining point and release bubble from the joining point. Figure 4.19 (a) shows the porosity amount is higher when electrode angle is higher. Which is not good for the welding joint. In Figure 4.19 (b), the porosity amount is lower when electrode angle is lower so for better welding joint electrode angle should be maintained lower. Figure 4.19 (c) shows the irregular and porous welded joint when the process is without oscillation.

V_A =20µm, V_F =150 Hz,
W_S = 3.5mm/sec, E_A=33.1^0 (Sample No.24)
(a)

V_A =20µm, V_F =150 Hz,
W_S = 3.5mm/sec, E_A=11.9^0 (Sample No.23)
(b)

V_A = 0, V_F = 0,
W_S = 2.0mm/sec, E_A=33.1^0 (Sample No.40)
(c)

Figure 4.5.s : Change of Porosity amount with the change of electrode angle (a) high porosity (b) less porosity (c) Highly porous (no oscillation).

Figure 4.17 (b) & Figure 4.18 (b) represent that with high frequency and high amplitude, less electrode angle provides greater penetration in joining point. Because more metal is entering and metal is getting enough space to reach the lower point of the joint. Therefore, penetration increases, so the bending strength of this joint becomes high. Figure 4.20 (a) shows high electrode angle with low amplitude and frequency decreases bending strength but less electrode angle with high amplitude and frequency increases bending strength shown in Figure 4.20 (b). Figure 4.20 (c) shows the incomplete penetration when the welding process is without oscillation.

V_A =20µm, V_F =150 Hz, W_S = 3.5mm/sec, E_A=33.1^0 (Sample No.24)
(a)

V_A =20µm, V_F =150 Hz, W_S = 3.5mm/sec, E_A=11.9^0 (Sample No.23)
(b)

V_A = 0, V_F = 0, W_S = 2.0mm/sec, E_A=33.1^0 (Sample No.40)
(c)

Figure 4.5.t : Penetration change with electrode angle (a) less penetration (b) high penetration (c) less penetration (no oscillation).

Figure 4.17 (c) & Figure 4.18 (c) show that with the decrease of electrode angle, having high vibration frequency and high vibration amplitude and less welding speed, deposition rate gets higher. Because high frequency and high amplitude provides less porosity and high penetration. As the porosity becomes lower in the molten material and metal is entering more into the joining point.

V_A =15µm, V_F =200 Hz,
W_S = 5.0mm/sec, E_A=30^0 (Sample No.15)
(a)

V_A =15µm, V_F =200 Hz,
W_S = 5.0mm/sec, E_A=15^0 (Sample No.7)
(b)

V_A = 0µm, V_F = 0,
W_S = 2.0mm/sec, E_A=30^0 (Sample No.39)
(c)

Figure 4.5.u : Change of deposition rate with the variation of electrode angle (a) low deposition rate (b) high deposition rate (c) low deposition rate (no oscillation).

Figure 4.21 (a) & (b) show how deposition rate varies with high and low electrode angle and in Figure 4.21 (c), it can be seen that without oscillation less deposition rate occurs which is not good for the joint.

Figure 4.17 (d) & Figure 4.18(d) shows less electrode angle with high frequency, amplitude and less welding speed gives more dilution cause for higher penetration and less porosity in the joining point, amount of hot metal increases into the joining point and so it can dilute more area than high electrode angle with oscillation.

V_A =20µm, V_F =150 Hz, W_S = 3.5mm/sec, E_A=33.1^0 (Sample No.24)

(a)

V_A =20µm, V_F =150 Hz, W_S = 3.5mm/sec, E_A=11.9^0 (Sample No.23)

(b)

V_A = 0µm, V_F = 0, W_S = 2.0mm/sec, E_A=30^0 (Sample No.39)

(c)

Figure 4.5.v : Change of dilution with the variation of electrode angle (a) lower dilution (b) higher dilution (c) lower dilution (no oscillation).

Figure 4.22 (a) shows welding with high electrode angle dilutes less area than welding with less electrode angle shown in Figure 4.22 (b). In Figure 4.22 (c), it shows dilution percentage is very low when the welding process is without oscillation.

4.6 Concluding remark

From the above discussion, it can be easily said that those input parameters- Amplitude, Frequency, Welding speed, Electrode angle have a very significant effect on welding process. Analysis of variance (ANOVA) has been done for all the output parameters using the calculated values from experiments. This ANOVA study is done to generate model equations for every output parameters. These model equations have been used to find out the relation between input and output parameters through graphical analysis. Graphical analyze of input and output parameters shows that hardness of a welded joint increases when the amplitude, frequency, welding speed and electrode angle in a selected range. Hardness differs with the amount of porosity in welding section. If porosity amount is higher in welded section, hardness becomes low and if this porosity amount is lower, hardness of the joint gets higher. This study also shows the similar phenomenon with the other output parameters – bending strength, deposition rate and dilution. Vibration amplitude, frequency, welding speed and electrode angle control penetration level in welded joint. These controlled input parameters in some specific ranges helps to get complete penetration in joining section, which provides the better joint than regular cases.

Chapter 5 Analysis and results obtained from ABAQUS

This chapter shows the results that were obtained using ABAQUS software. The analysis that was done, was used to check the measure of heat transfer, and the stresses that were experienced by the model. The software itself is a product of Dassault Systemes, and has many applications when it comes to computer aided design and analysis.

5.1 Heat Transfer Model

The ABAQUS software uses a special plugin that is used to conduct an analysis on a model that is being welded. The plugin, ABAQUS welding Interface (AWI) was used for the majority of this analysis. A job was created and a section was assigned. The maximum and minimum flame temperature was set, and the increment temperature was also set. A nodal finite analysis was conducted and the result showed the variation of heat flux in every node that was assigned. The figures below show the variation in heat flux.

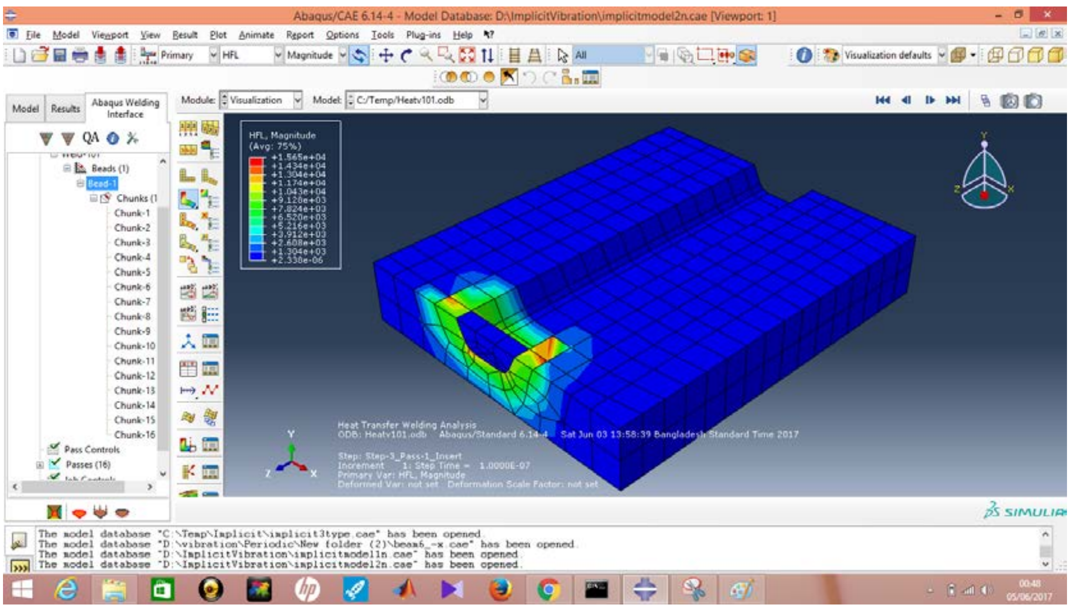


Figure 5.1.a: Distribution of heat flux along the model

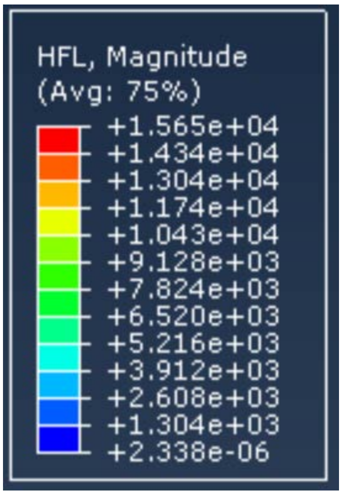


Figure 5.1.b: Values of the4 heat flux

5.2 Stress Analysis Model

A model was created, with sections assigned. Some material properties were set such as conductivity, expansion coefficient, mass density, specific heat, yield stress and young modulus. After that, a nodal finite element process was initiated on the model. The result showed a figure depicting the Von Mises Stress on different nodes on the model.

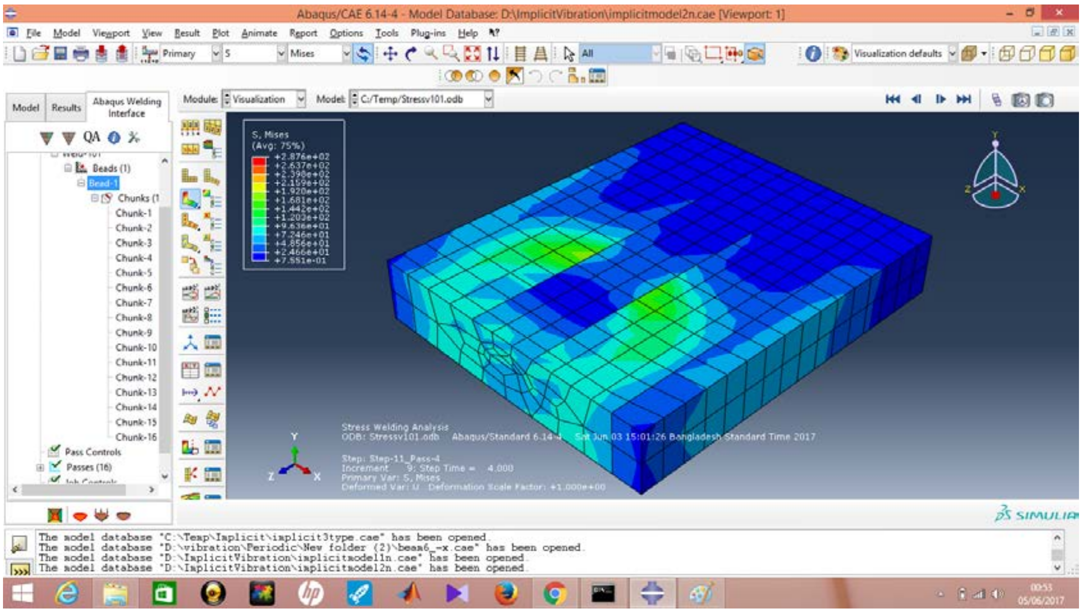


Figure 5.2.a: Von Mises Stress distribution

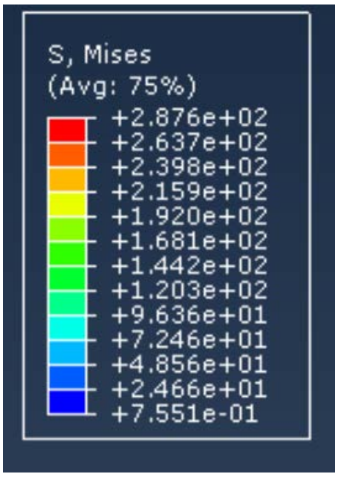


Figure 5.2.b: Von Mises stress values

5.3 Von Mises Stress pattern under vibration

The stress analysis was once again conducted on the model, but this time it was done under the influence of a periodic vibration. The frequency and amplitude of the vibration was set, as well as the boundary conditions for the model. Many test runs were conducted with varying frequencies (such as 50hz, 75hz, 100hz, 150hz). The diagram below shows the stress analysis distribution when the vibration was set to be 100hz.

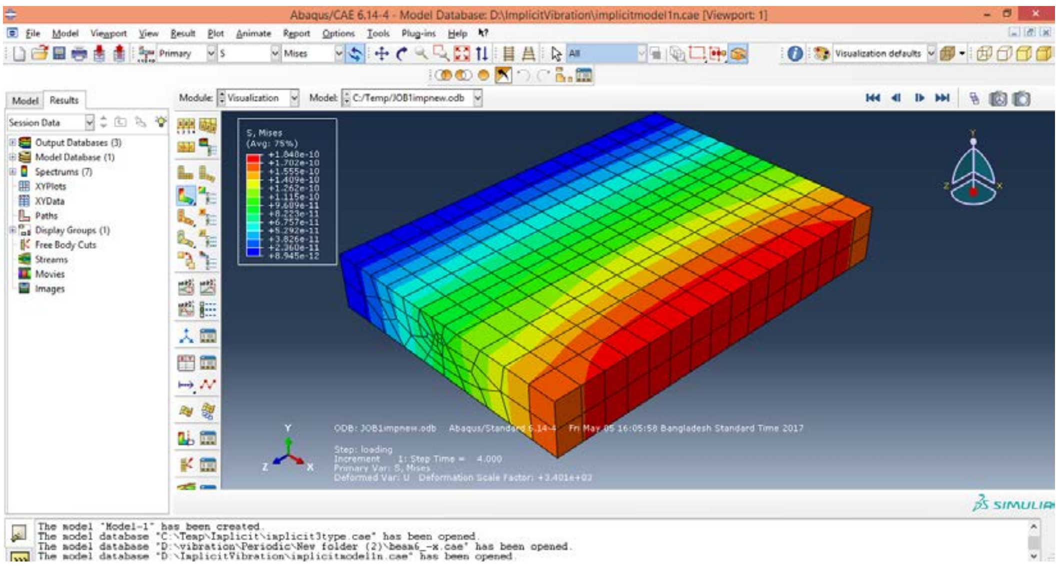


Figure 5.3.a: Von Mises stress on vibration model

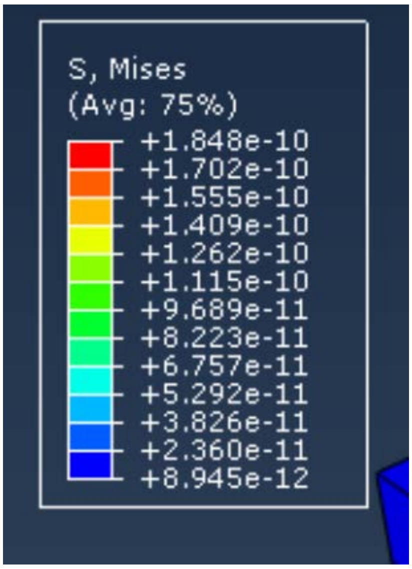


Figure 5.3.b: Von Mises stress values

5.4 Conclusion based on software results

Based on the series of analysis that were conducted by ABAQUS, it was observed that there were no changes in the heat flux in either case (with vibration or without). However, there were observable changes in the residual stresses that resulted on the job. When vibration was applied, it was seen that the stresses on the job were less than the case when vibration was absent. This is good, as weld joints are not weakened and results in a reliable weld with a higher life cycle.

Chapter 6 Conclusions, Contributions and Recommendations

This chapter summarizes the conclusion of the experiment (section 5.1) and discusses research contributions of this work (section 5.2). Limitations of the present work and suggestions are discussed in (section 6.3).

6.1 Conclusion

Welding is a process of joining two metals but different welding processes have different strength quality. This quality of strength depends on many parameters like dilution rate, deposition rate, welding angle, welding speed etc. Oscillation assisted welding process is a modified process to improve the quality of welds in arc welding through improving mechanical properties such as hardness, bending strength, deposition rate, dilution etc. Literature review shows properly designed and fabricated oscillation assisted arc welding systems can enhance product quality. Few oscillations assisted welding experiments has been done using ranges of different parameters. In this study, some input parameters like vibration amplitude, vibration frequency, welding speed and electrode angle are selected to analyze the variation in welded joint and output parameters – hardness, bending strength, deposition rate and dilution are selected. Different ranges of parameters are set to analyze the changes of mechanical properties of the joining section. At first, a design is established based on the concept of the experiment. According to the design, an experimental set up is established. Then several welding processes with oscillation have been conducted. After getting results, output parameters – hardness, bending strength, deposition rate and dilution are calculated. Analysis of variance (ANOVA) has been done for all the output parameters using the calculated values from experiments. This ANOVA study is done to generate model equations for every output parameters. These model equations have been used to find out the relation between input and output parameters through graphical analysis. Graphical analyze of input and output parameters shows that hardness of a welded joint increases when the amplitude, frequency, welding speed and electrode angle in a selected range. This study also shows the similar phenomenon with the other output parameters – bending strength, deposition rate and dilution. Vibration amplitude, frequency, welding speed and electrode angle control the penetration level in welded joint. These controlled input parameters in some specific ranges help to get complete penetration in joining section, which provides the better joint than regular cases. Actually, two types of data with and without oscillation are collected to compare with each other. At the end of the study, it becomes clear that oscillation within selected range is good for improving mechanical properties of joining section of the welded materials.

6.2 Research Contributions

- Better welding joint can be got by using this type of process and it is very important precise welding joint for space shuttle, highly sophisticated experimental tools etc.
- It can be useful in competitive Automobile factory to furnish its several parts.

6.3 Limitations and recommendations

There is no experiment, which has no limitations but overcoming the limitations with carefulness is necessary. The limitations of this experiment are given below:

- Any amount of vibrational amplitude is not helpful. There is a range of vibrational amplitude for this kind of experiment. The range of amplitude is 5–30 μm. within this range it gives good mechanical properties.

- Frequency range for this experiment is 80-400 Hz. Within this range, this experiment provides desired results. Too much frequency from this range will cause damage of the joining point.

- As more welding speed or electrode angle is not good for the welding process and very less welding speed or electrode angle will not provide any good mechanical properties. Therefore, while using those input parameters it should be set up carefully.

- Due to having lack of research facilities, there are other output properties like tensile strength, residual stress, toughness are not found out and analyzed and those properties are important parameters for welding joining point. Using vibration in welding process, better outcome can be hoped for those parameters.

Chapter 7 Bibliography

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