LUT UNIVERSITY
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THE EFFECT OF TILTING ANGLE ON PENETRATION DEPTH AND PROFILE IN LASER WELDING AND IN SUBMERGED ARC WELDING

Examiner(s): Professor Harri Eskelinen
Kari Erik Lahti

ABSTRACT

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The effect of tilting angle on penetration depth and profile in laser welding and in submerged arc welding

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There are many factors on which the penetration depth in Submerged Arc Welding and laser welding depends upon. Tilting angle of incidence is one of the important factors on which the penetration depth depends on. There are two ways of doing welding: one is at pull angle and another is at push angle. Penetration depth largely depends on these pull and push angle. Penetration depth will not be same for pull and push angle even if the angle of incidence is same.

This thesis studies the effect of tilting angle on penetration depth in submerged arc welding and laser welding. The material used for the welding is 500 ML of thickness 24 mm. The experiment is done in two parts with two sets of parameters: first being submerged arc welding with the angle of incidence of 0°, 10° and 20° keeping all other parameters fixed. Similarly, laser welding is done with the angle of incidence of 0°, 10°, 15° and 20° and again with all other parameter fixed. After the experiment, the parts were taken through number of post processing steps like sawing, grinding, polishing, etching before taking the microstructure picture for measuring the penetration depth. The results from the experiment verifies the finding from the literature review that the penetration depth on SAW (push angle) and laser welding (pull angle) is maximum at 0° and it keeps on decreasing as the angle of incidence keeps on increasing.

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I am grateful for my father, brother, sisters who supported me in every step of my life. This would not be possible without their love, support and care. Lastly, I would like to thank all my friends who supported me directly or indirectly throughout my journey.

Krishna Pandey

Krishna Pandey

Lappeenranta 19.11.2019

DEDICATION

In memory of my loving mother

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LIST OF SYMBOLS AND ABBREVIATIONS

Ar	Argon
BP	Beam Power
BW	Bead Width
CO_2	Carbon dioxide
DOP	Depth of Penetration
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
HSS	High Strength Steels
SAW	Submerged Arc Welding
WS	Welding Speed

1 INTRODUCTION

1.1 Introduction of thesis topic

Submerged Arc Welding (SAW) and laser welding are two types of welding with high possibilities and high productivity compared to other welding process. These both welding methods has characteristics which are different from each other. Some of the most important comparison between these two are shown in table below.

Table 1: Comparison of laser welding and submerged arc welding [1].

	Laser Welding	Arc welding
Gap bridging	➢ Poor gap bridging ➢ Narrow fusion zone	➢ Good gap bridging ➢ Wide fusion zone
Residual stress and distortion	➢ Low heat input ➢ Low distortion ➢ High residual stress	➢ High heat input ➢ High distortion ➢ Low residual stress
Cooling rate	High cooling rate	Low cooling rate
Reflective materials	Difficult to weld	Weldable
Formation of welds	Porosity in deep penetration	Less porosity
Weld penetration	➢ Deep weld pool ➢ Single pass welding of thick sections ➢ Multiple pass welding can be used of thicker sections if external filler is used	➢ Relatively shallow fusion zone ➢ Multiple pass welding
Productivity	High productivity because of high welding speed	Low productivity because of low welding speed.

To achieve the desired quality of the final workpiece; proper selection of different paraments is necessary. Tilting angle of welding head is one of the important parameters which play a major role in achieving the desired quality of the workpiece. The selection of proper tilting angle depends on many factors like the workpiece material, reflectiveness of the material. Tilting angle of welding head has various effects on the workpiece like the depth of penetration and the quality of the weld. Penetration depth varies as the angle of incidence of welding head varies. The quality of the weld is also largely depending on the parameters including angle of incidence used during the welding. So, this research is focused on finding out the effect of different angle of incidence on penetration depth in laser welding and in SAW.

1.2 Structure of thesis

The first chapter of this thesis is introduction which explain the description of thesis, structure of the thesis, background of the research, objectives of the research, methods used in the research and research questions. The second chapter include theorical background and brief description of the research findings which is related to this thesis.

The third chapter of the thesis is the experimental part. The experimental part includes the welding of the 24 mm workpiece with the help of laser welding and submerged arc welding with varying angle of incidence. The fourth chapter present the results and analysis of the results obtained from the chapter three. The next chapter is conclusion which concludes this thesis. The chapter six is the final chapter of this thesis work which suggest on the further research topics raised during the completion of this thesis work.

1.3 Background of the research and motivation

This thesis work is part of the research project about the possibilities and challenges of laser submerged arc hybrid welding commercially. This research is a part of Ph.D thesis about laser submerged arc hybrid welding for Mr. Kari Erik Lahti of AB Bayrock, Sweden. The project is carried out in cooperation of Laboratory of Welding (Lappeenranta University of

Technology) and AB Bayrock Sweden. The primary objectives of this project are to achieve different findings like effects of different parameters on welding, finding out imperfections which occurs during the welding and cost estimation of the welding. This thesis is focused on finding the effect of tilting angle on penetration depth in laser welding and submerged arc welding.

The experiment is done in a way to support the project of laser submerged arc hybrid welding which means that the laser will be leading the process. The laser welding in this thesis is done in pulling angle and submerged arc welding is done in pushing angle which is typically the combination of laser submerged arc hybrid welding to have maximum penetration.

1.4 Objectives of the research

The main objective of this research is to study the effect of angle of incidence of welding head on penetration depth and profile in laser welding and submerged arc welding. The research will help to find the proper angle of incidence of welding head to achieve the maximum penetration and desired quality of weld on the workpiece.

The research mainly focused on finding the proper angle of incidence for 500 ML steel of 24 mm to have the maximum penetration with other parameters being fixed.

1.5 Methods used in the research

The methods used in this research are literature review and experimental part. In the literature review different factors which affects the quality of weld are studied. Moreover, different effects of angle of incidence on penetration depth, weld profile and welding process are also studied for laser welding and submerged arc welding. In the experimental part the effect of different angle of incidence 0°, 10°, 15° and 20° on penetration depth are studied.

1.6 Research questions

- What is the effect of tilting angles on penetration depth and profile in laser welding and in submerged arc welding?
- What will happen to the quality of weld with increasing and decreasing of angles

2 LITERATURE REVIEW

2.1 Laser welding

Laser welding is the welding process in which the two materials are joined because of the continuous heat input from the concentrate coherent beam to the surface of the workpiece. In this process laser beam of very high intensity is focused on the surface of the workpiece with the help of laser nozzle. Then it melts the metal on the top part of the work piece and some part of metal is vaporized. When the power density exceeds its threshold level then the keyhole is formed which is also called as keyhole welding [2]. The laser weld setup and process are also explained in the figure below.

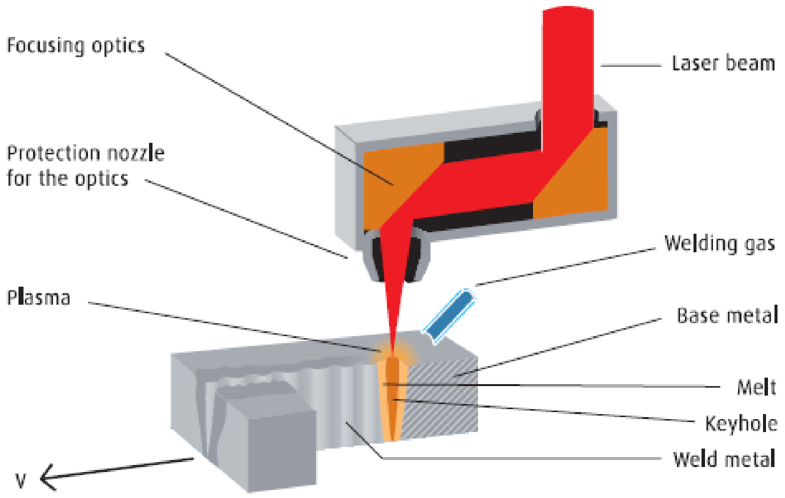


Figure 1: Keyhole welding [3].

The different kinds of laser which are used in welding are described below [4] [5] [6]:

- Gas lasers

  These are those types of laser which use mixture of different gases such as helium, nitrogen, Carbon dioxide (CO_2). These lasers typically use high power source and low voltage to excite the mixture of the gas.

- Solid states lasers (Nd:YAG and ruby lasers)

  Solid states lasers are those types of laser which operates at 1 micrometer wavelengths and can pulsed or operate continuously.

- Diode lasers

  These are the types of laser which uses electrical energy as energy sources and convert that into light.

2.1.1 Advantages of laser welding

There are different advantages of laser welding over tradition welding methods. The heat amount that is needed in laser welding is low and also the heat affected zone is narrower than other conventional method. Moreover, the amount of imperfections and distortion is low. Laser welding are also used for welding of two metals which are not similar. So, they will have more range in terms of acceptance of weld materials. Unlike other traditional welding method filler material is not needed in laser welding. Furthermore, the quality of the weld is higher and the quality of finishing is so good that the finishing operation is not needed in laser welding like other conventional welding processes [6] [7].

2.1.2 Disadvantages of laser welding

Alike every processes laser welding also has some disadvantages. Compared to other welding processes the initial investment cost is much higher in laser welding though they increase productivity eventually when use in mass scale. Moreover, when the workpiece is cooled rapidly it may cause some cracks on the workpiece. Furthermore, the optical surfaces of the instrument are prone to damage, so they are always at high risk [6] [7].

2.1.3 Factors affecting penetration and profile of a weld in laser welding

There are different variables on which the penetration and profile of a weld in laser welding depends such as laser power, welding speed, wavelengths, beam diameter, beam quality, shielding gas, focused power density, defocused distance, material properties.

The figure below shows the effect of use of different shielding gases on penetration for type 304 welds which are made with CO_2 laser of 10kW power. It shows that the penetration is higher when using helium gas as shielding gas and it keeps on decreasing with increasing amount in gas ratio of Ar to He [8-12]. When using N_2 gas as shielding gas the penetration is shallower than He [13].

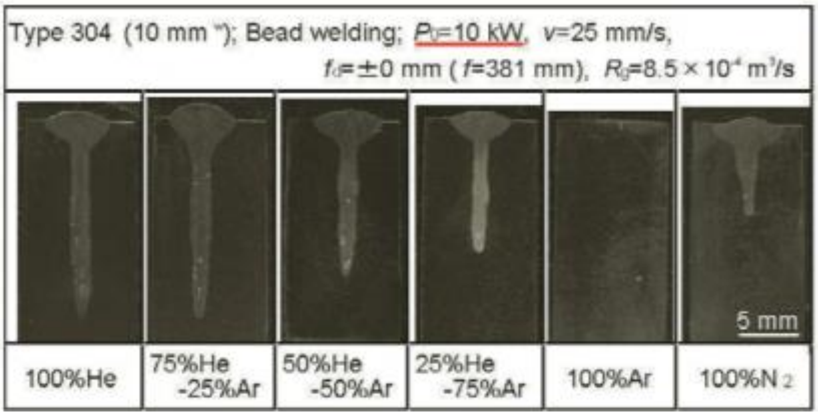


Figure 2: Effect of shielding gas on penetration depth [13].

The below figure shows the weld profile and penetration while welding with fiber laser of 2 to 10 kW power in Ar shielding gas. It reflects that the penetration is increased with increasing laser power. It also further shows that the deep penetrated weld is also possible with Ar shielding gas in fiber laser welding. So, while comparing this with above figure: it was known that the effect of shielding gas is noted with CO_2 laser of about 10.6 μ m wavelength at higher speeds but not so greatly affect with fiber laser of about 1.07 μm wavelength. [9] [11] [13].

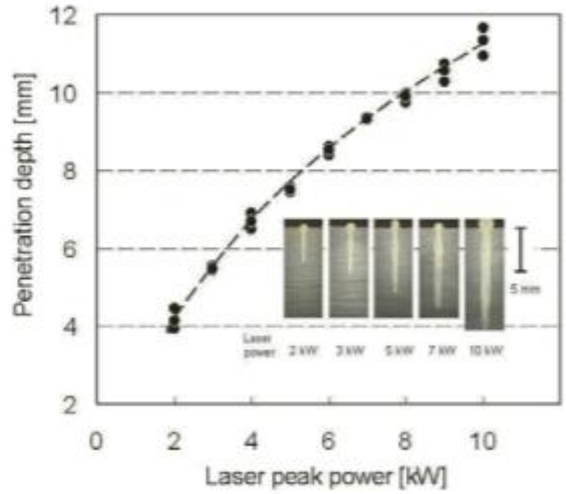


Figure 3: Penetration depth in laser welding in relation to laser power [9] [11].

The figure below shows the effect of different beam diameter and welding speed on penetration depth of weld beads. It reflects that the smaller beam diameters of higher power densities produce the maximum penetration depth at higher welding speeds. It further shows that deeper penetration welds are achieved at lower speeds and also the effect of power density is lesser at lower speeds. Here the effect of defocused distance on penetration is also studied which reveals that the deepest penetration is achieved when the focal point is under the specimen surface, but the welds are shallower because of longer defocused distance [9] [14].

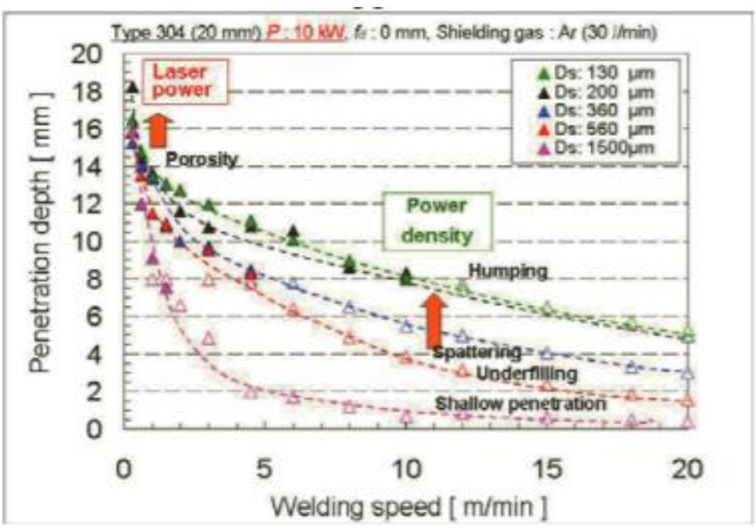


Figure 4: Effect of beam diameter and welding speed on penetration depth [9] [14].

2.1.4 Factors affecting the laser weld quality

The figure below which is Ishikawa diagram describes best about the different factors affecting the quality of the weld in laser welding. The figure shows the main branches which are further consisted of different parameters which may directly affect on formation of microstructures and geometry of weld. So, the selection of the welding parameters is very important to obtain the desired quality of the final weld with excellent mechanical properties and minimum distortion. As per the figure the main factors which influence in the quality of the weld are as follows:

- Laser Source
- Beam Parameter
- Mechanical Parameter
- Shielding Gas
- Parent Materials
- Jigs, fixture and tooling
- Joint Design
- Beam positioning (welding position, beam incident angle, defocusing etc.) [8] [13].

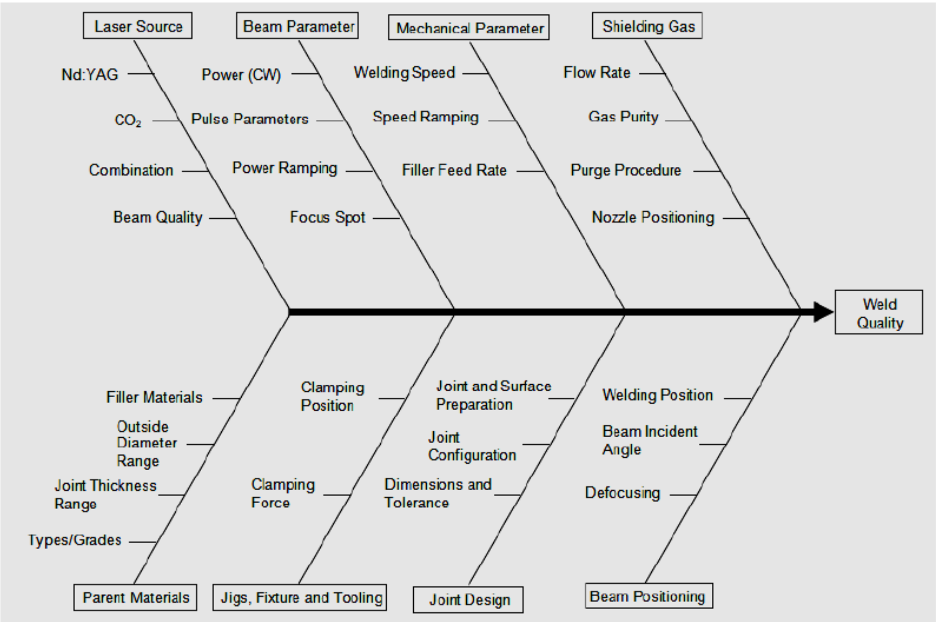


Figure 5: Ishikawa diagram showing the factors affecting the laser weld quality [8].

2.2 Submerged arc welding

Submerged arc welding (SAW) is the high productivity welding process which form arc with continuously fed wire and the workpiece. The actual welding takes place under the layer of powdered flux which is fed from the hooper. As the arc is submerged beneath the flux during the whole process so the arc is not visible during the welding which is also shown from the figure below. The main essential equipment involved in SAW are power source, SAW head, flux hopper, protective equipment [15].

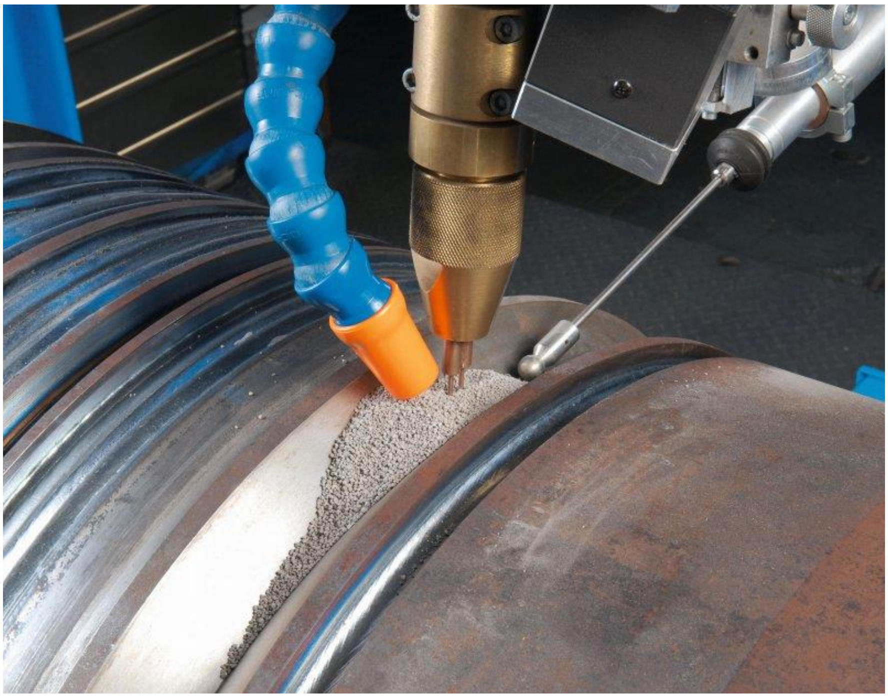


Figure 6: Submerged arc welding [16].

2.2.1 Advantages of SAW

There are many advantages of SAW compared to other welding process. Firstly, this process has high deposition rate. They can deposit typically upto 45kg/h. This process has ability to penetrate deeper on the workpiece compared to other workpiece as they generally use high power source. During the welding operation arc light and welding fumes emitted in this process is minimum. SAW has high degree of freedom as this process is suitable for both outdoor and indoor works. Furthermore, it is possible to obtain high quality weld. The flux used in the process can be recovered, recycled and reused upto 50-90% [13] [15] [17].

2.2.2 Disadvantages of SAW

There are few disadvantages of SAW as well. This process is generally limited to thick materials and also on top of that SAW is only limited to ferrous (steel or stainless steel) and some nickle-based alloys. The welding operation can be only done either in flat or horizontal position. One of the major disadvantages is about health issue as the flux and slag used during the operation can be toxic [13] [15].

2.2.3 Application of SAW

Typically SAW is used in industrial purposes such as structural and vessel construction. It is also used in chemical plants (boilers, pipes) and on shipbuilding. Different materials that can be used in SAW applications are carbon steels, low alloy steels, stainless steels, nickel-based alloys [17].

2.2.4 Factor affecting penetration depth in submerged arc welding

There are different factors that affects the penetration depth in submerged arc welding. The penetration depth generally depends on the welding speed, polarity, current, electrode angle and energy density of the arc. The penetration is generally increased with the increasing energy density.

Welding speed

The depth of penetration depends on the welding speed. Moreover, welding speed has also affect on the overall shape and profile of the weld. With the high welding speed, thin and shallow penetration of weld profile is obtained whereas with the low welding speed, wide and deep penetration profile is obtained as shown in figure below [18] [19].

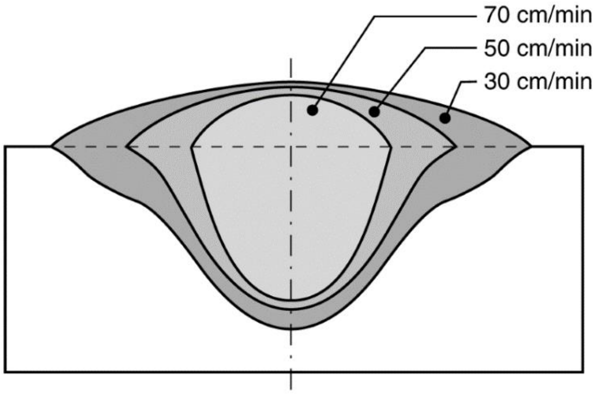


Figure 7: Effect of welding speed on penetration depth in SAW [19].

Current and voltage

The final shape of the weld is determined by the current and voltage supplied. The depth of the penetration is controlled by current whereas voltage determine the width of the weld. Figure below show the effect of the current to the final weld of the workpiece. The figure shows that with the increasing current the depth of penetration is increasing [19].

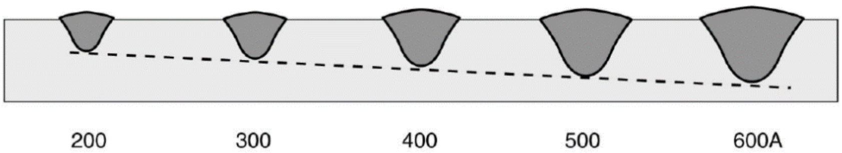


Figure 8: Effect of current on the weld of a workpiece in SAW [19].

However, the current that can be used depends on the diameter of electrode used in submerged arc welding. If the current is too high then different kinds of problems like burn through owing to deep penetration, residual stresses and weld distortion will occur. Furthermore, if the current is too low than different kinds of problems like lack of penetration, lack of fusion, unstable arc will occur. So, the approximate combination of proper electrode diameter and welding current is presented in the table below. [18] [19].

Table 2: Appropriate electrode diameter in relation to welding current

Diameter (mm)	Welding Current (A)
1.6	150-300
2.0	200-400
2.5	250-600
3.15	300-700
4.0	400-800
6.0	700-1200

Similarly, the figure below shows the effect of voltage to the final weld of the workpiece. The figure shows that: with the increasing voltage, the width of the weld is increasing whereas the voltage does not have much effect on depth of penetration.

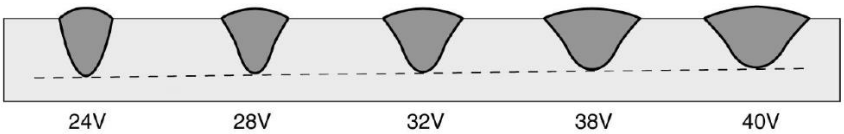


Figure 9: Effect of voltage on the weld of a workpiece in SAW [19].

Polarity

The figure below describes that there is high difference in depth of penetration with the positive and negative polarity of the electrodes while welding with direct current, DC. The reason behind the higher depth of penetration with positive polarity is because of phenomenon of increase in heat development that comes along with positive polarity. So, by such way less amount of material will be transferred but penetration depth will be higher. On the contrary when the welding is done with negative polarity the amount of material that is transferred is higher, but the penetration depth will be lower and also the arc stability is less [19].

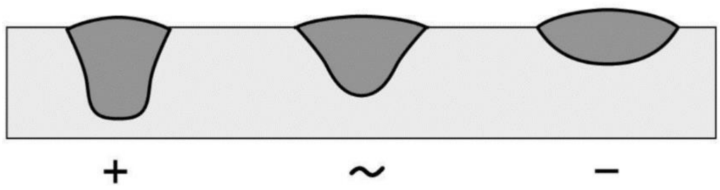


Figure 10: Effect of polarity on penetration depth in SAW [19].

Electrode diameter

The depth of penetration also depends on the diameter of electrode used during the submerged arc welding. The figure below shows that the depth of penetration decreases with the increasing electrode diameter for a given welding current. The larger diameter electrode is generally selected for depositing larger amount of material and have a better gap bridgeability [19].

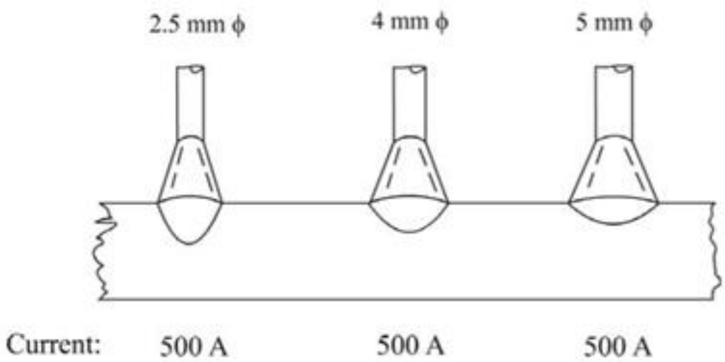


Figure 11: Effect of electrode diameter on penetration depth in SAW [19].

2.3 Effect of tilting angle of laser beam in laser welding

2.3.1 Angle of incidence of laser beam on penetration

(Unt, Lappalainen and Salminen, 2015) studied the effect of welding parameters on weld bead profile when welded with laser for the material AH36 of 8 mm. They studied by welding the plates of T-joint configuration. They varied 3 different angles 6°, 10°,15° and observed the weld profile of the plate. At first, they fixed the angle to 6° and the beam was focused 0.5 mm above the joint. The welding speed they used was 1.25 m/min and then they increased the beam angle to 10° and 15° respectively. They were able to achieve full penetration when the beam angle was 6° but when they gradually increased the angle the penetration depth kept on decreasing. The reason was that in case of 6° the enough melt was pushed through root side whereas when the angle is increased it did not happen. When the angle is increased beam will miss the plane creating under-fillings so fusion zone will not get to root region. Therefore, increasing the angle from 10° to 15° the area of fusion zone kept on decreasing. The effective throat with the 10° was 6.8mm whereas the effective throat with 15° was 4.3 mm HAZ area remaining same [20].

They concluded that the reason for decreasing penetration with increasing angle is because of the beam being more absorbed in melt when inclination angle is adjacent to the joint.

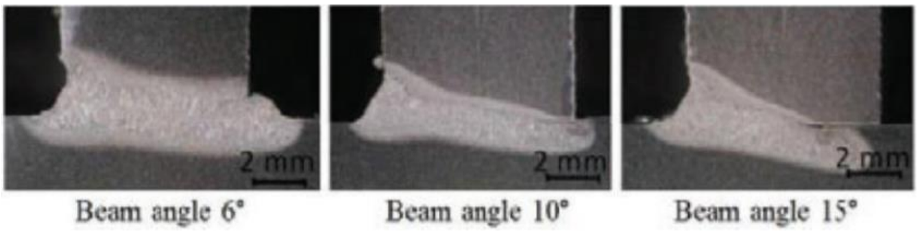


Figure 12: Beam behavior at different angles [20].

2.3.2 Angle of incidence of laser beam on weld bead and penetration

In another study (Siva et al., 2009) performed an experiment to find the influence of beam incidence angle in laser welding using finite element analysis. They performed an experiment with the commercial AISI 304 austenitic stainless steel of 3.15 mm thickness by using Nd:YAG laser of maximum 2kW power continuous wave mode. The different beam incidence angle they choose are 5°, 10° and 15°. They performed the experiments in 3 different levels with 3 different laser power 600, 1000, 1400W and 3 different welding speeds 0.8, 1.4 and 2m/min which is shown by table below [21].

Table 3: Three different level parameters used in experiment

Parameters Level	Beam Power (BP), Watts	Beam Angle (BA), degrees	Welding Speed (WS), mm/min	Glass flow rate (GF), 1/min	Spot diameter (SD), mm
I	600	5	800	5	0.8
II	1000	10	1400	5	0.8
III	1400	15	2000	5	0.8

They especially studied the effect of angle of incidence of laser beam on the bead geometry by using the finite element analysis. The figure below shows the macrograph photograph when the constant 0.8 m/min welding speed is used at different welding laser power and different angle of beam incidence. Digital image inspection system is used to measured weld bead dimension. The figure shows the depth of penetration (DOP), bead width (BW) and depth of penetration to width ratio (d/w). In the first part of the figure below DOP is 0.27 mm, BW is 0.95 mm and d/w is 0.28 when 600 W laser power, 0.8 m/min welding speed and angle of beam incidence is 15 degrees. Similarly, when the welding power is 1000 W, welding speed of 0.8 m/min and 10 degrees of incidence angle 0.66 mm of DOP, 1.05 mm of BW and 0.62 of d/w is achieved. Highest DOP of 1.15 mm and BW of 1.15 mm with d/w ratio of 1 is achieved with the 1400 W laser power, 0.8 m/min welding speed and 5 degrees of incidence angle.

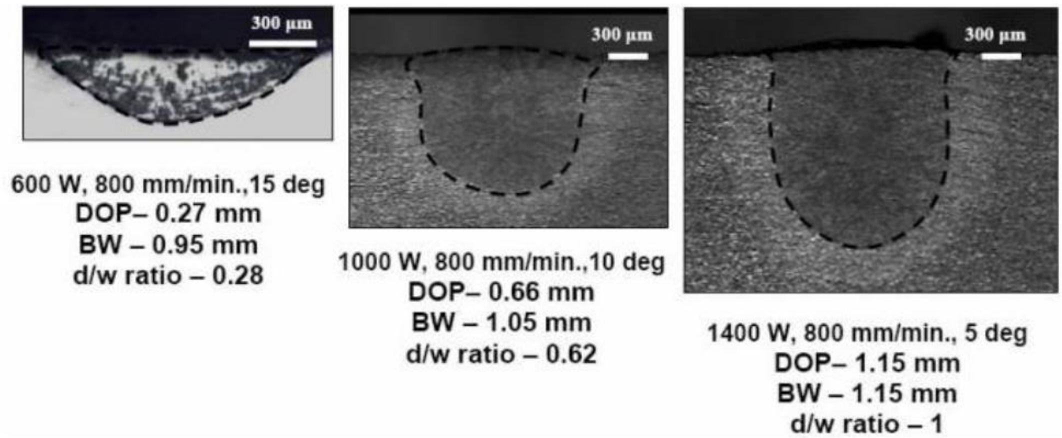


Figure 13: Macrograph photograph of weld profile with constant 800 mm/min speed [21].

The figure below shows the cross section of the bead at constant welding speed of 0.8 m/min. In this figure the depth of penetration and weld bead width are shown along the vertical and horizontal direction respectively. It can be seen from the figure that as the laser power increases from 600W to 1400W weld dimension changes drastically. Higher penetration and wider width are obtained with increasing laser power.

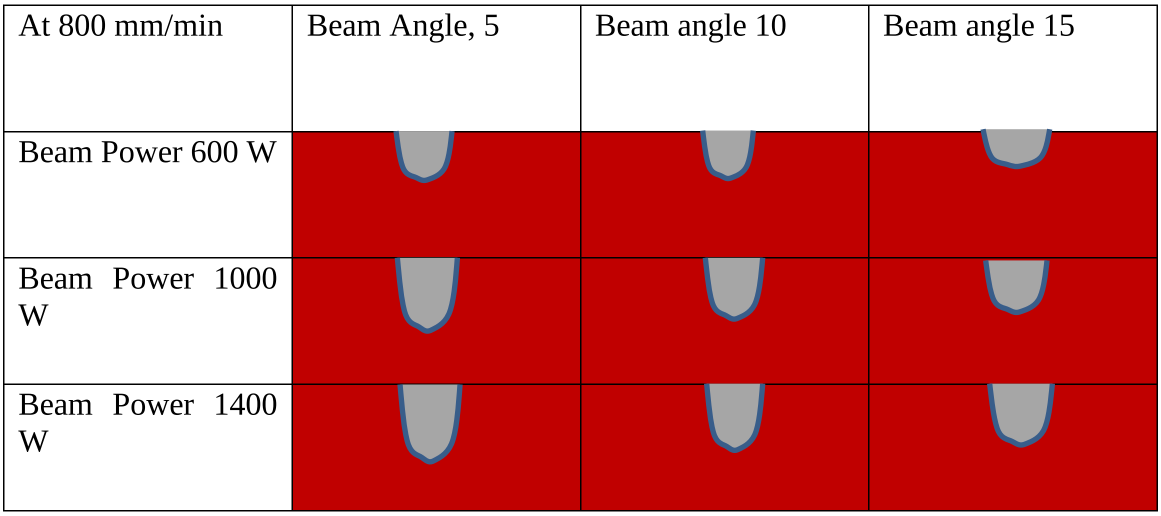


Figure 14: Cross section of bead at constant welding speed of 0.8 m/min [21 revised].

The figure below shows the cross section of bead at constant welding laser power of 1400 W. It can be seen from the figure below that the penetration depth changes drastically as the beam angle is increased from 5º to 15º at different welding speeds. It shows that the penetration depth decreases with the increasing welding speed at these angles with the given power of 1400W.

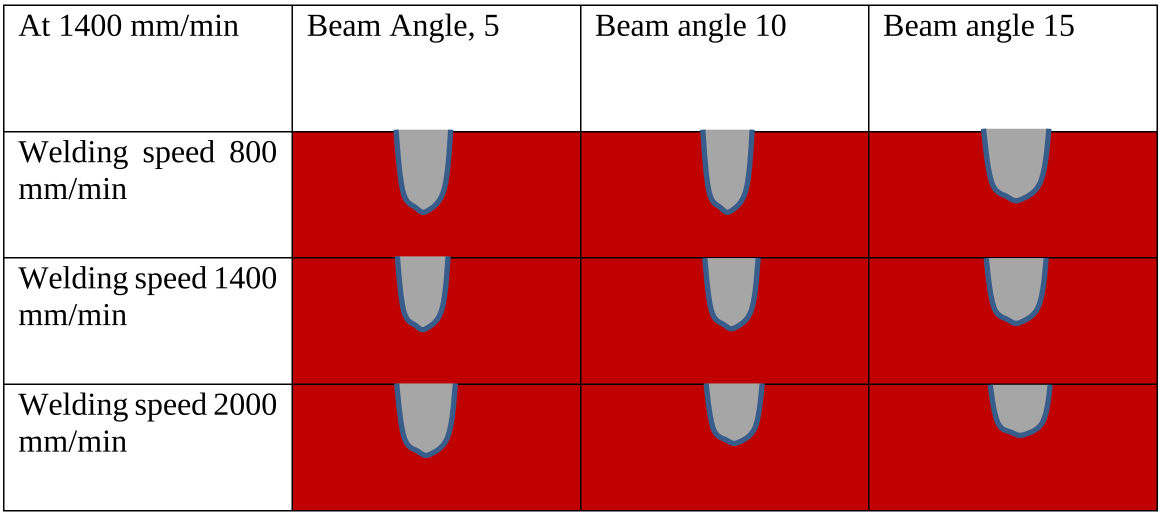


Figure 15: Cross section of bead at constant welding power of 1400W [21 revised].

2.3.3 Angle of incidence on welding process

(Drechsel et al., 2013) performed an experiment to find out the effect of angle of incidence on welding process. They performed experiment with two kinds of steel grades which are stainless steel SS 304 and a cold-rolled steel 22MnB5 of different thickness from 1 to 3 mm. The laser power used was 1.84 kW and welding speed of 18m/min [22].

In deep penetration welding, the formation of plasma is obvious which adversely influence the welding process at high welding speed in terms of humping free weld seams. These can be controlled by changing the angle of incidence of laser beam which reduces plasma interaction with laser radiation. The figure below best describes the welding speed and it’s relation to plate thickness in terms of formation of humping and humping free weld seams.

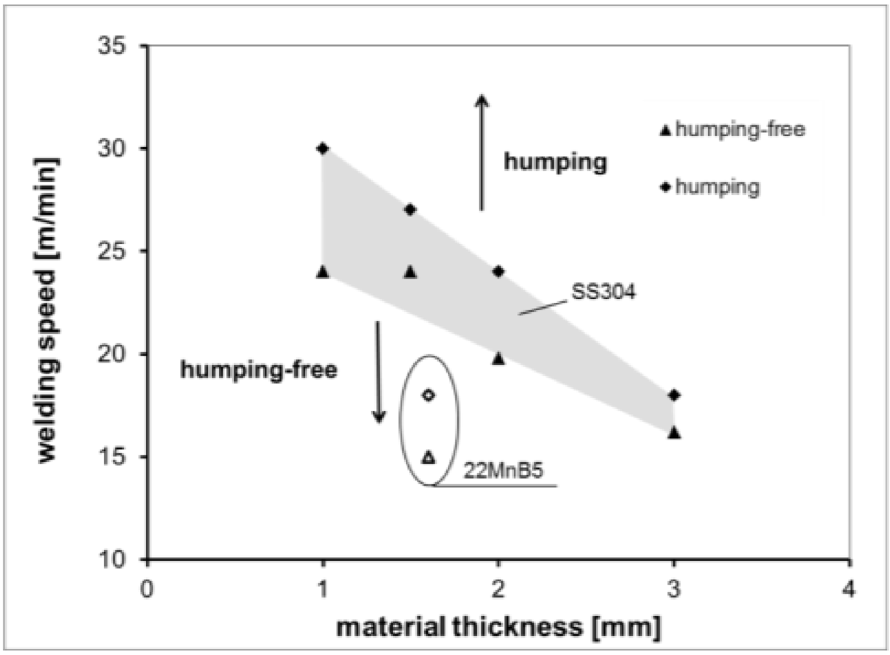


Figure 16: Relation between welding speed and material thickness in terms of humping and humping free weld seams [22].

The figure below shows the demonstration of angle of incident and orientation of preferred plasma plume (upper row) and photographs of observed orientation of plasma plume during welding process. The figure demonstrates that the orientation of plasma plume varied in different direction to the laser beam without preferred orientation with the tilting angle less than 25 degree. When the tilting angle of laser beam is increased from 25 degrees plasma plume is formed on the other direction of laser beam. It was noticed from the experiment that if the angle of incidence is above 45 degree than the material cannot be welded anymore.

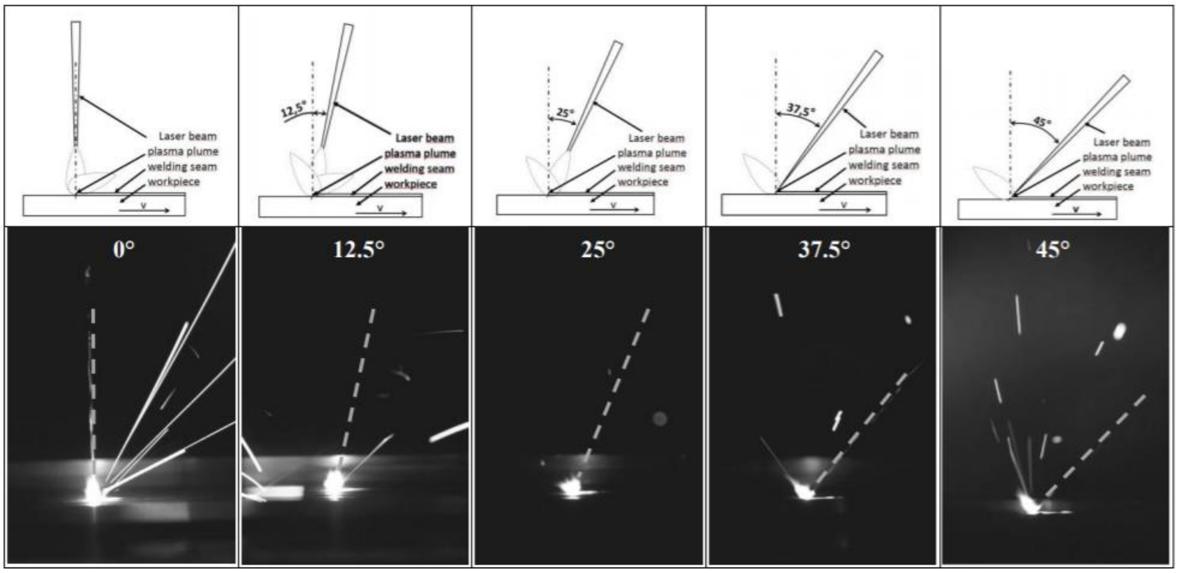


Figure 17: Demonstration of angle of incident and orientation of preferred plasma plume and photographs of observed orientation of plasma plume during welding process [22].

The figure below shows different tilting angle of laser beam incident in relation to welding speed and laser power for achieving humping free weld seams. The below figure shows that the laser power must be adjusted as the inclination angle is increased.

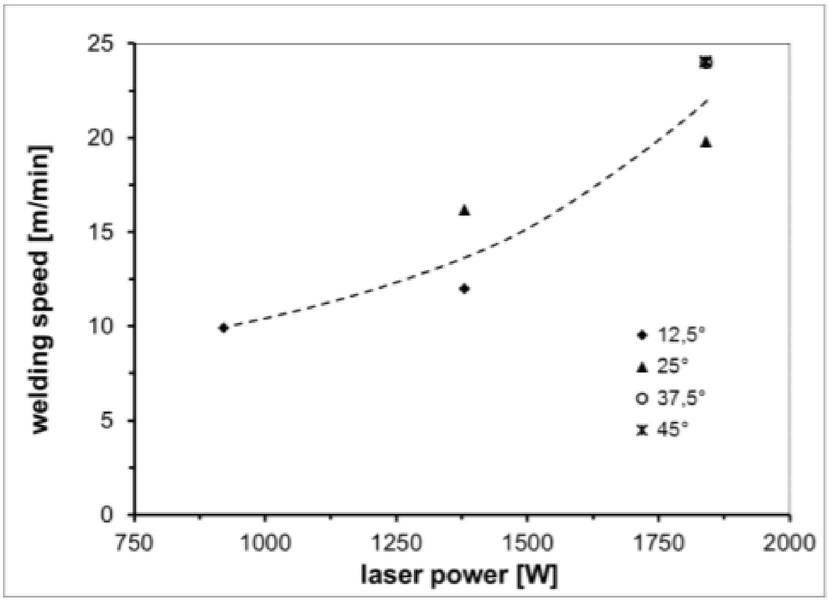


Figure 18: Maximum welding speed allowing humping- free weld seams in relation to angle of incidence and laser power [22].

2.4 Effect of tilting angle of welding torch in Submerged arc welding

2.4.1 Effect of tilting angle on penetration depth of Submerged arc welding

In submerged arc welding the electrode can be placed in three different ways: perpendicular to the workpiece, tilted forward (backhand welding) and tilted backward (forehand welding) with relation to weld pool. The weld pool shape, weld bead geometry and penetration are different in each case.

In forehand welding the electrode is tilted backward which means towards already deposited bead. In this welding the molten metal flows under the arc reducing the depth of penetration while increasing the width of the weld [23].

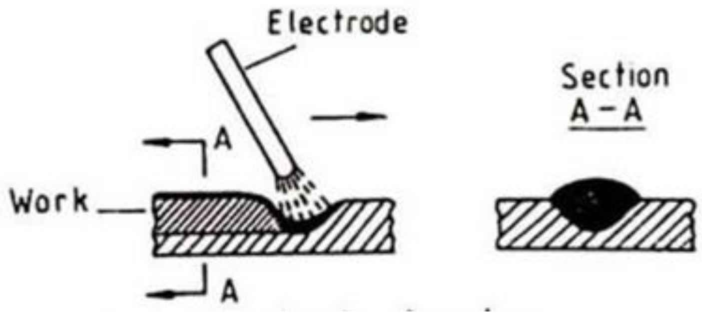


Figure 19: Forehand welding [23].

In backhand welding the electrode is tilted forward which means towards the seam to be welded. In this welding the molten metal from beneath the arc is scooped because of the pressure of arc resulting in deep penetration while reducing the width of the weld.

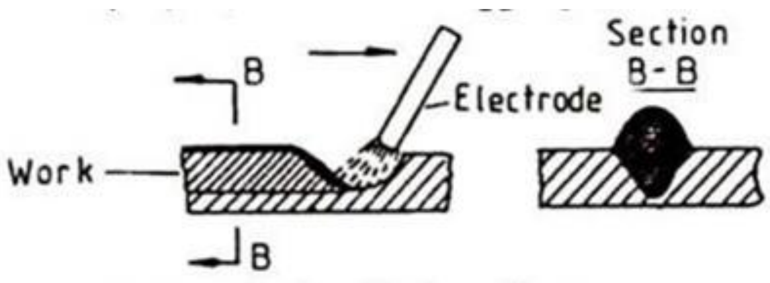


Figure 20: Backhand welding. [23].

When the electrode is perpendicular to the workpiece, the penetration is little smaller than backhand welding and higher than in forehand welding. Similarly, the width of the weld is smaller than forehand welding and bigger than in backhand welding. The below figure summarizes the above mentioned all three types of welding with the penetration level and the size of width of the weld.

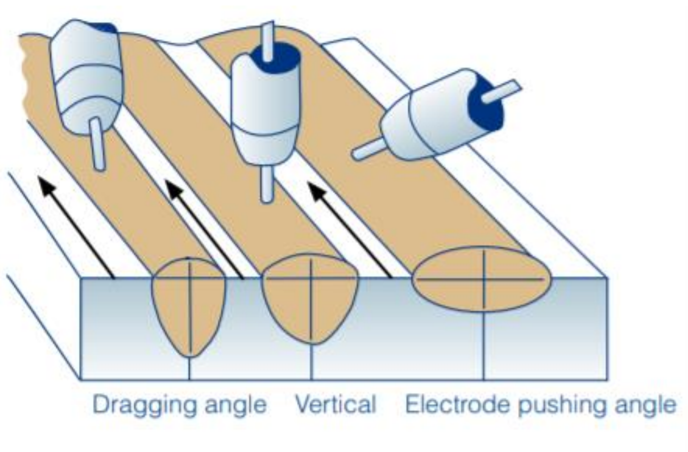


Figure 21: Effect of different welding types in penetration depth and profile in SAW [20].

It was found from the literature review [20] that the penetration depth in dragging angle (pulling angle) keeps on increasing as the angle decrease from 90°. It will keep on increasing up to certain angle and then the penetration depth will again decrease from that certain angle. On the contrary, in case of pushing angle the penetration depth is maximum when the angle of incidence is 90° from the surface of workpiece. As the angle decreases the penetration depth keeps on decreasing. But in case of horizontal vertical fillet welds the deepest penetration is achieved when the angle is smaller as shown in figure below.

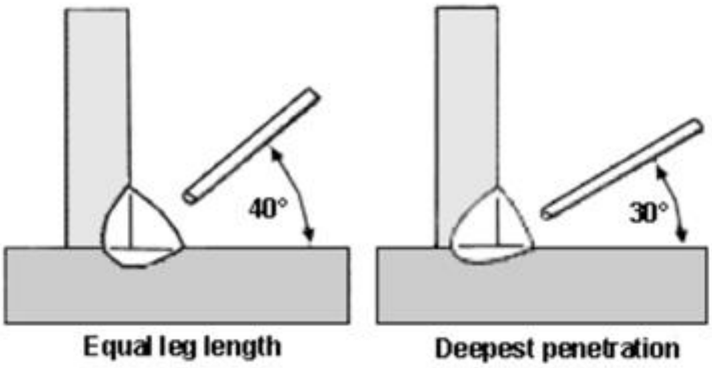


Figure 22: Effect of tilting angle in horizontal vertical fillet welds in SAW [20].

2.4.2 Effect of work angle on penetration in Submerged arc welding

Penetration in submerged arc welding also depends on the angle of work position. There are three kinds of welding: uphill welding, flat welding and downhill welding. The work can be positioned in these three ways as per the need of penetration depth of the workpiece. The penetration depth is shallower in downhill welding as the molten metal flows under the arc similar to forehand welding. However, in case of uphill welding the molten metal from beneath the arc is scooped because of the pressure of arc increasing the depth of penetration. The tilting angle of the work cannot exceed 6° to 8° as there will be lack of fusion or irregular bead geometry will occur. [9].

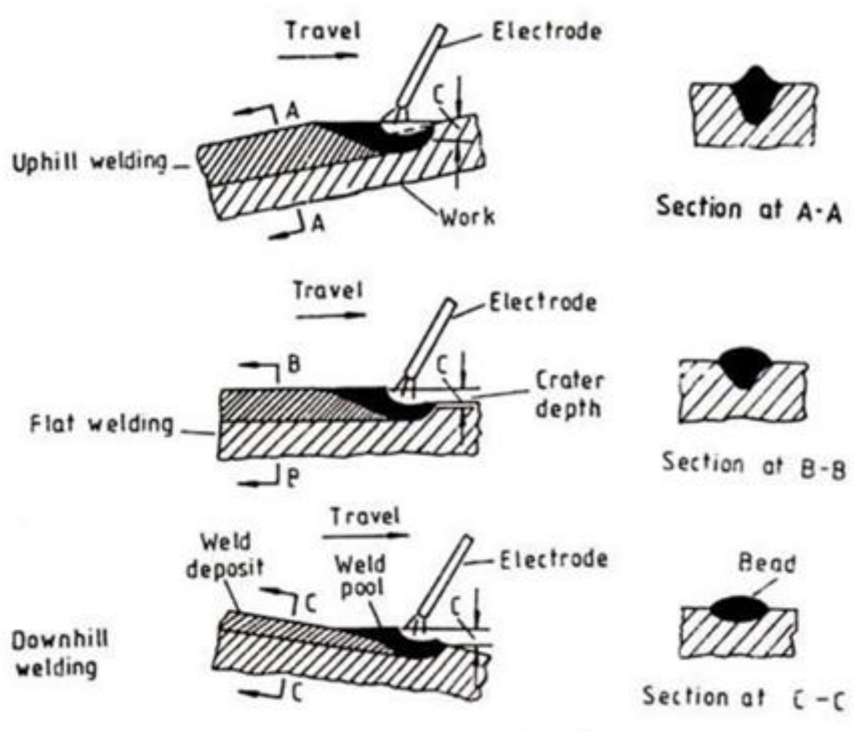


Figure 23: Effect of work position on penetration depth in SAW [9].

2.4.3 Torch angle and position in arc welding

Effect of electrode to work angle on weld geometry using GMAW.

(Ghazvinloo et al., 2010) performed an experiment to find the effect of electrode to work angle while welding HQ130 steel plates of 5 mm thickness by using robotic Gas Metal Arc Welding (GMAW). After the experiment the relationship between penetration depth with the electrode angle is studied along with filler diameter. The electrode angle chosen are 65°, 75° and 85° and the filler diameter chosen are 0.8, 1, 1.2 mm. The shielding gas used are Ar, He and CO_2 as shown in table below [24] [25].

Table 4: Variable parameters of experiment [24].

Parameters	Value
Angle of the electrode	65°, 75°,85°
Diameter of filler material (d)	0.8, 1, 1.2 mm
Type of shielding gas (S:G)	Ar, He, CO_2

The parameters that are kept unchanged throughout the welding process is shown in table below.

Table 5: Unchanged parameter of the experiment [24].

Parameters	Limit/Type
Cylinder pressure (bar)	135
Cylinder outlet pressure (L/min)	14
Nozzle opening (mm)	10
Electrode stick out (mm)	15
Arc length (mm)	3
Nozzle to work distance (mm)	16
Arc voltage (V)	23
Welding current (A)	140
Welding speed (cm/min)	60
Wire feeding rate (m/min)	8
Droplet transfer	Spray transfer mode
Polarity	DCEP

A total of 9 different experiments is done for measuring penetration depth with the three electrodes to work angle, three filler diameter and three shielding gases. The 3 figures below show the result on penetration from the experiment.

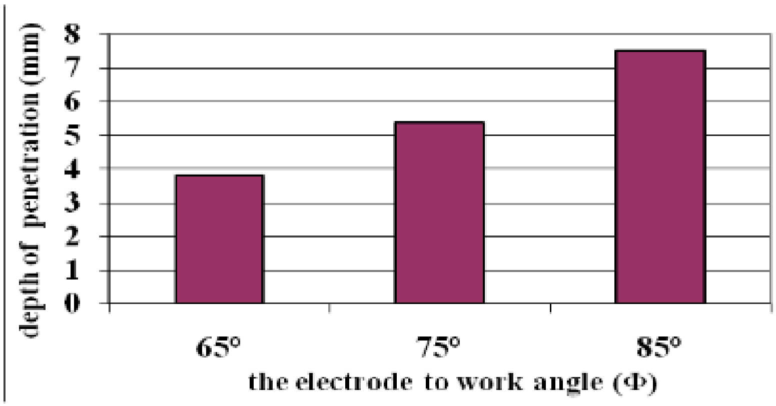


Figure 24: Depth of penetration and electrode to work angle when using 1.6mm filler diameter and CO_2 gas [24] [25].

The above figure shows the depth of penetration in relation with electrode to work angle with CO_2 as shielding gas and 1.2 mm filler diameter. The figure shows that penetration depth is increasing with the increasing work angle from 65° to 85° having exact values of 3.81, 5.38 and 7.50 mm.

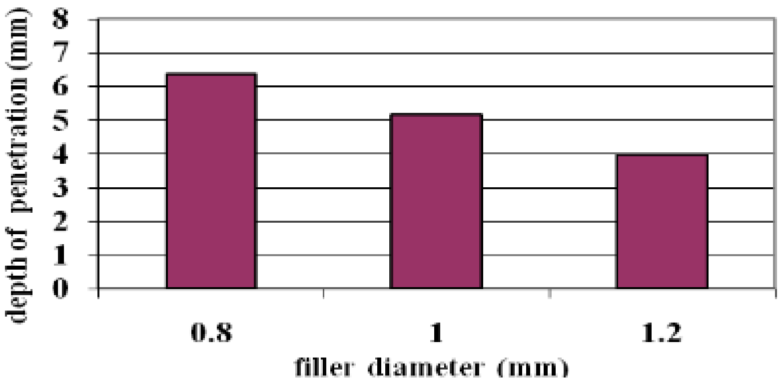


Figure 25: Penetration depth and filler diameter when electrode angle is 85° with CO_2 as shielding gas [24] [25].

The above figure shows the relationship between penetration depth and filler diameter at constant 85° electrode to work angle and CO_2 as shielding gas. It shows that depth of penetration is decreasing with increasing in filler diameter from 0.8 to 1.2 mm.

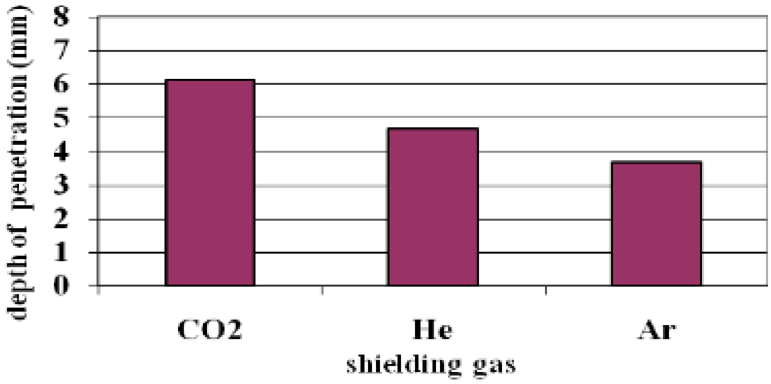


Figure 26: Depth of penetration and shielding gas when electrode angle is 85° with 1.2 mm filler material diameter [24] [25].

The above figure shows the relationship between depth of penetration and shielding gas at constant 85° electrode to work angle and 1.2 mm filler diameter. It shows that depth of penetration is highest for CO_2 and lowest for Ar [24] [25].

2.5 Comparison of effects of tilting angle on penetration depth in laser welding, submerged arc welding and GMAW welding.

The literature review from above suggest that in case of laser welding the maximum penetration depth can be achieved when the beam is perpendicular to the surface of the workpiece. As the angle keeps on decreasing the penetration depth keeps on decreasing until it reaches to angle 45°. The research finding from above suggest that once the tilting angle comes below 45° than the material cannot be weld anymore.

In Submerged arc welding and GMAW welding it was found from the above literature finding that the penetration depth keeps on increasing when the angle of welding torch decreased from 90° to 80° in case of pulling angle. Once it reached tilting angle of 80° it will have maximum penetration. When the angle of welding torch decreases from 80° then the penetration depth keeps on decreasing. However, in case of pushing angle the maximum penetration is achieved when the welding torch is perpendicular to the workpiece. Penetration depth keeps on decreasing once the angle is decreased from 90 degrees.

2.6 Welding of High Strength steels

2.6.1 HSS

High strength steels are those kinds of steels which are mainly used construction or structural applications. That is why they are also called as structural steels. These steels can be produced with or without microalloying element according to the application. HSLA which is commonly known as high strength low alloy steels are typically produced with the help of microalloying elements like chromium, molybdenum, nickel, copper, vanadium, zirconium, etc as per the property needed for the application. These added microalloying elements offer high strength, good formability and good weldability [26] [27].

2.6.2 Guidelines to weld HSS

There are few guidelines or rules which will help welder to achieve a desired weld quality. Here are few steps to follow to achieve sound weld:

- The first step is finding the proper procedure from the concerned authority or from the manufacturer in welding the high strength steels. If the welder doesn't pay enough attention in finding the proper procedure it may results in cracking, degradation of the surrounding parent metal, reduced joint strength.

- The electrodes that are used for welding must be clean. If the steel yield strength more than 690 MPa then the electrodes must be baked at temperature 370-425 C for about an hour before used.

- While welding it is better to weld with small electrodes using stringer beads rather than weaving technique which limits heat input alloying steel to achieve full strength.

- The part to be weld or the area to be welded must be cleaned properly. If there is anything like paint, dirt, rust, oil or other foreign objects it must be cleaned properly otherwise it will cause porosity or the welding is more susceptible to cracking.

- If the material required pre heat and post heat treatments the material must be heated evenly throughout the thickness of the material. If the material is heated at high temperature than the strength of steel can be reduced.

- The location of the welding platform also plays a role in achieving quality weld. When welding in low ambient temperature like in winter it might create cracks due to quenching of weld metal quickly.

- After the final welding the weld quality must be examined which can be done by magnetic particle inspection. As hydrogen cracking occurs once the weld has cooled it is better to examine the weld after 48 hours from the welding time as hydrogen cracking can be formed up to 48 hours [28] [29].

2.6.3 Challenges of welding HSS

There are various challenges associated with the welding of high strength steels. Some of the problems includes cracking, residual stresses, distortion, fatigue damage. Within these the most common type of problem is cracking. The reason behind this crack is due to the stress exceeding the ultimate tensile strength of the weld metal. This crack can be divided into two categories: [30] [31] [32].

Hot Cracks

Hot Cracks are usually present on the weld bead and HAZ. When they are present on the weld bead they are called as Solidification cracks but when they are present on HAZ they are called as Liquation Cracks [30] [32].

Cold Cracks

Cold Cracks also called as Hydrogen Induced Cracking (HIC) or delayed cracking are those kinds of cracking which are developed because of diffusible hydrogen content, high hardness, susceptible microstructure. Typically, the reasons of cold cracking in high strength steels are the least understood of all weld cracking [30] [32].

3 EXPERIMENTAL PART

At first the experiment is performed with SAW and then with laser. For SAW, welding tractor is used. The different essential components used in SAW are:

Table 6: SAW welding component

Power Source	Pandaweld
Welding tractor	Pandaweld
Welding head	Pandaweld
Flux	ST55 (EN ISO 14174: SA FB 1 55 AC(D) H5)
Electrode wire	Topcore 742B (EN ISO 26304-A: S 69 6 FB T3Ni2, 5CrMo
Material	500 ML (EN 10029)
Material thickness	24 mm

The welding head and the welding tractor used in the experiment are as shown in the figure below.

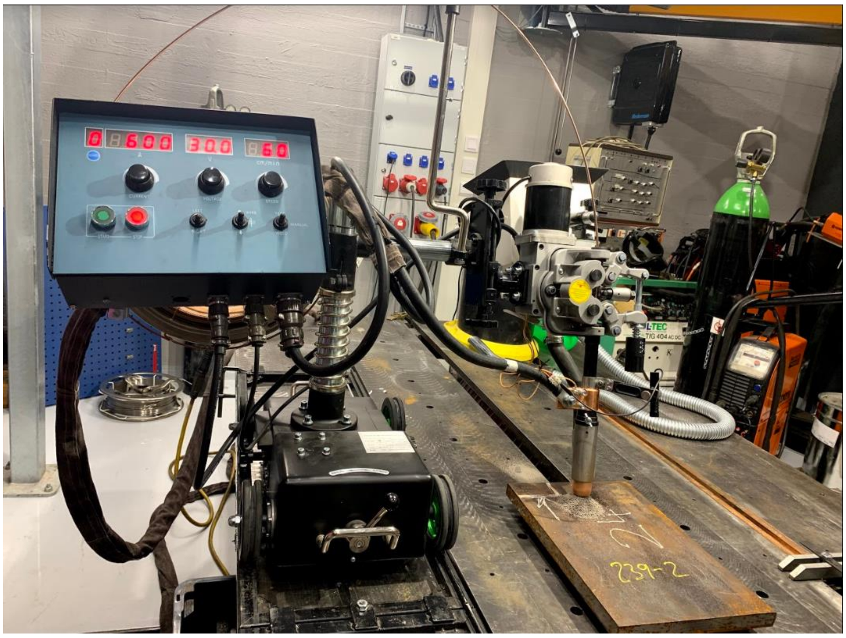


Figure 27: SAW tractor

The power source used in the experiment is from the pandaweld as shown in figure below.

Figure 28: SAW Power source

The flux used in the experiment is ST55 which is high basic SAW flux with very low hydrogen content. Due to it's low hydrogen content, this can be used for multilayer welding in high demanding offshore applications. More information about ST55 flux is attached at the appendices.

The electrode wire that is used is Topcore 742B which is high basicity flux-cored wire. This type of electrode has high level of crack resistance in addition with the very low content of Hydrogen. This electrode is suitable for welding HSS as they have excellent weldability for structural steels. More information about Topcore 742B electrode is attached in appendices.

The workpiece material used is 500 ML of 24 mm thickness. 500 ML is thermomechanically rolled steel which consists low carbon equivalent, so it provides excellent weldability property. Therefore, it is one of the most demanded steel for the complicated design structure in many fields like construction, mechanical engineering, offshore construction, ship building, storage tanks.

The chemical composition of the material is shown in the table below [33]:

Table 7: Chemical composition of material

C	Si	Mn	P	S	Al	Ni	Cu	Mo	Cr	V	Nb	Ti
≤0.09	0.15-0.55	1.00-1.75	≤ 0.020	≤ 0.005	≤ 0.02	≤ 0.70	≤ 0.35	≤ 0.35	≤ 0.35	≤ 0.08	≤ 0.05	≤ 0.025

The maximum carbon content of 500 ML is shown in the table below [33].

Table 8: Carbon content of 500 ML

Plate thickness t (mm)	CEV_1	CEV_2	CET	Pcm
t ≤ 50	0.45	0.47	0.30	0.24
50 < t ≤ 75	0.47	0.49	0.31	0.24

The minimum yield strength, tensile strength and minimum elongation is shown from the table below [33].

Table 9: Properties of the material

Plate thickness t (mm)	Minimum Yield Strength R_{eH} (MPa)	Tensile Strength R_m (MPa)	Minimum Elongation A5 (%)
t ≤ 16	500	610-750	17
16 < t ≤ 50	490	610-750	17
50 < t ≤ 75	480	600-750	17

The experiment is carried out for 3 different angles 0°, 10° and 20° at push angle while keeping all the other parameters unchanged. The maximum penetration occurs when the workpiece is perpendicular to the welding head which means at 0° and gradually with the increasing angle, penetration depth keeps on decreasing. So, to verify that we wanted to choose few angles from which we could see the change in penetration depth, so we choose three different angles at equal interval.

Table 10: SAW welding parameters

Angles	Current	Voltage	Welding speed	Electrode to work distance	Wire diameter	Heat Input
0°	600 A	30 V	60 cm/min	30 mm	4 mm	1.8kJ/mm
10°	600 A	30 V	60 cm/min	30 mm	4 mm	1.8kJ/mm
20°	600 A	30 V	60 cm/min	30 mm	4 mm	1.8kJ/mm

The heat input is then calculated with the help of formula mentioned below.

Heat input (H) = A* V* 0.06/v

In the above equation H refers to heat input, A refers to welding currents in Amps, V refers to arc voltage in volts and v refers to welding speed. 0.06 is for converting the final unit to KJ as the unit of Heat input is KJ/mm

Heat input = Current * Voltage *0.06/welding speed

Heat input = 600 A * 30 V * 0.06/600 mm/min

Heat input = 1.8 KJ/mm.

In case of butt welding the heat input with these parameters is much less than recommendation as it might not be enough to have desired penetration but as this was done on bead on plate, the penetration depth was not an issue. Here we are only concerned about having maximum penetration at certain angle than other angles.

A total of 3 test is performed with the above parameters. At first the welding torch is set perpendicular to the workpiece which means 0°. The first test is performed when the welding head is perpendicular to the workpiece. After finishing the first test the welding torch is set at 10° and welding is performed with 10°. Again, after finishing the second test the welding torch is set at 20° and the last test is performed with 20°. The angle is changed to verify the finding from the literature review [9] [21] that the penetration depth keeps on decreasing as the angle is increased.

The result from the above experiment is shown in figure below.

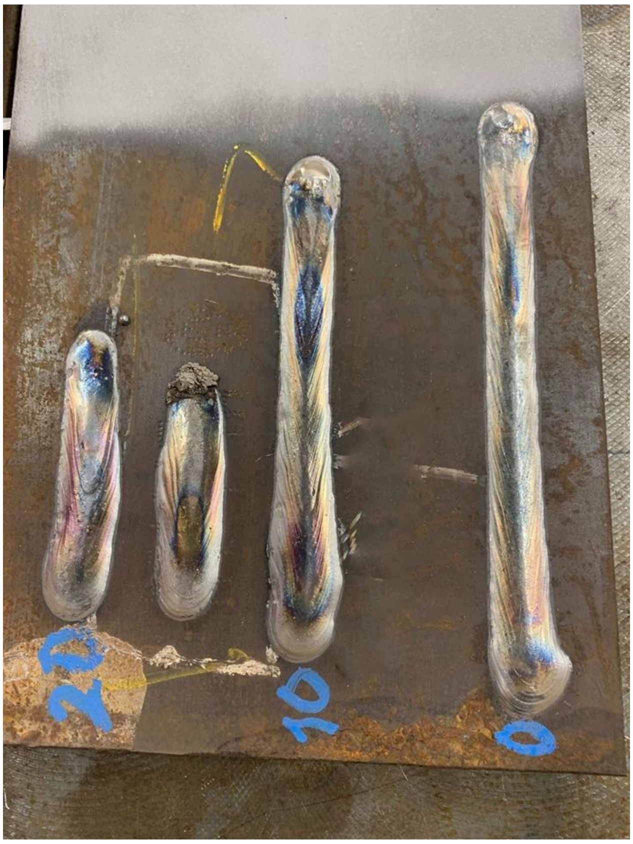


Figure 29: Final workpiece of SAW

After the welding, the welded parts are cut in small pieces to have the microstructure pictures with the help of automated saw. After cutting, the workpieces goes through different procedure like grinding, fine grinding, polishing and etching before actually receiving the microstructure pictures.

For grinding Struers TograForce-5 machine is used as shown in figure below.

Figure 30: Workpiece on grinding machine

The workpieces are grinded with the help of grinding machine as shown in the above figure. The parts are grinded until the smooth surface appears on the workpiece. The workpieces look like the picture below when they are ready for fine grinding.

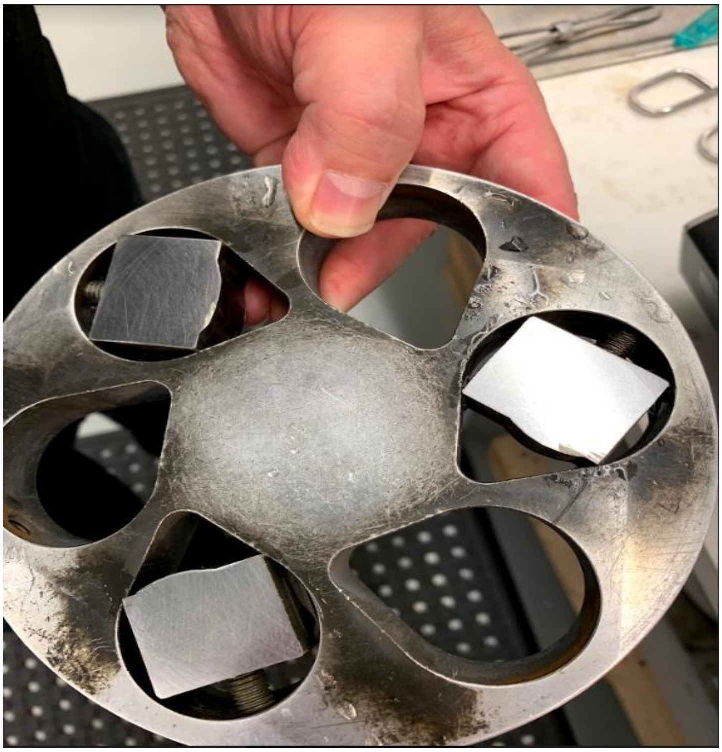


Figure 31: Workpiece after the final grinding operation.

The workpieces are then fine grinded with the help of grinding diamond which is followed by polishing with the help of polishing liquid. Once the polishing is done, workpieces are washed with clean water and soap. Moreover, after washing, ethanol is added to the workpieces and dried with the dryer. Etching process is performed after polishing and then the workpieces are again washed with the clean water and ethanol.

When all the steps mentioned above are followed then the final workpieces look like the picture below from where penetration depth can be clearly seen on the surface.

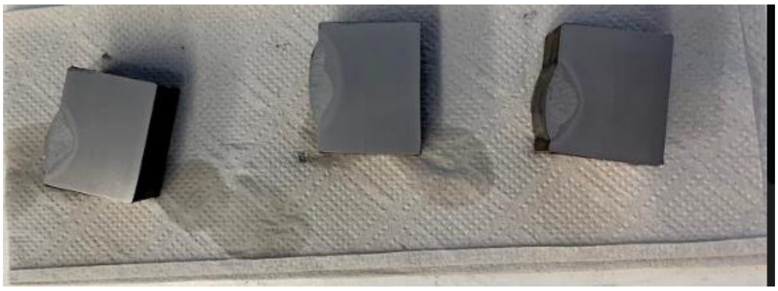


Figure 32: Workpiece that are ready for microscopic picture

After leaving the workpiece to dry up for some time, they are ready to take the microscopic pictures. The microscopic pictures for 0°, 10° and 20° are shown in the figure below.

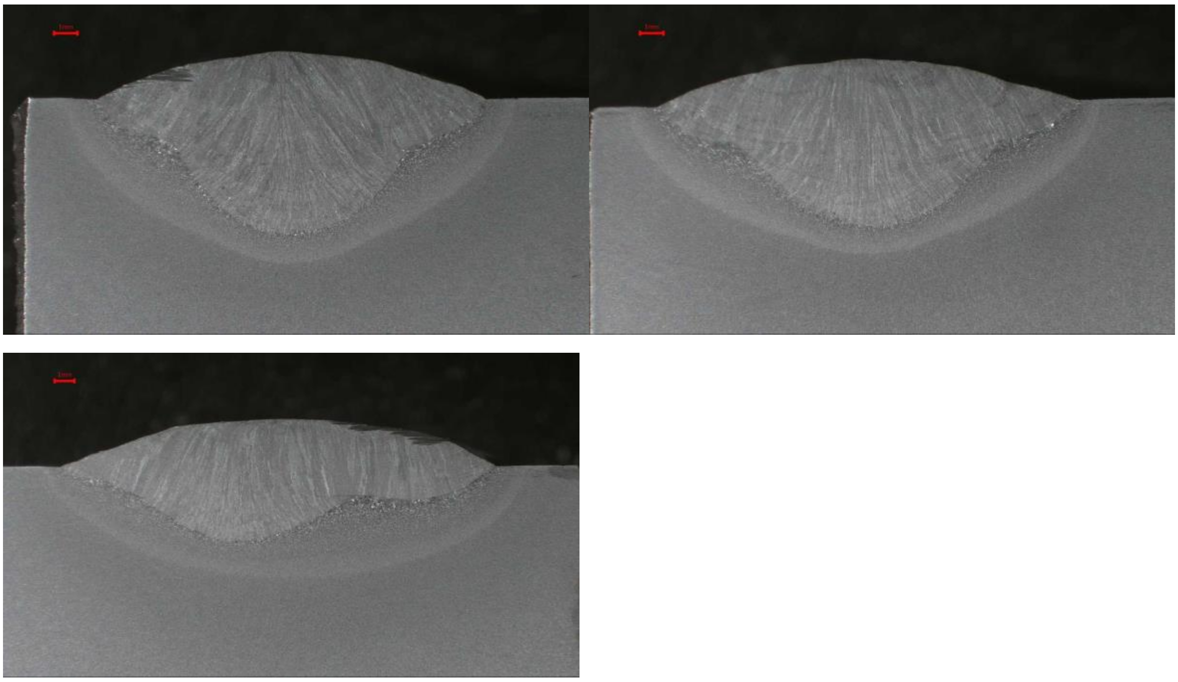


Figure 33: Microscopic pictures a) 0°, b) 10°, c) 20°

After finishing SAW, laser welding is done with the help of IPG 10kW fiber laser as shown in figure below. The description of the instrument used, and the parameters are shown in table below.

Table 11: Laser welding equipment

Laser	IGP 10 kW fiber laser
Welding head	Trumpf
Measuring scale	slant 100
Focus lens	300 mm
Collimation lens	200 mm
Fiber diameter	400 µm

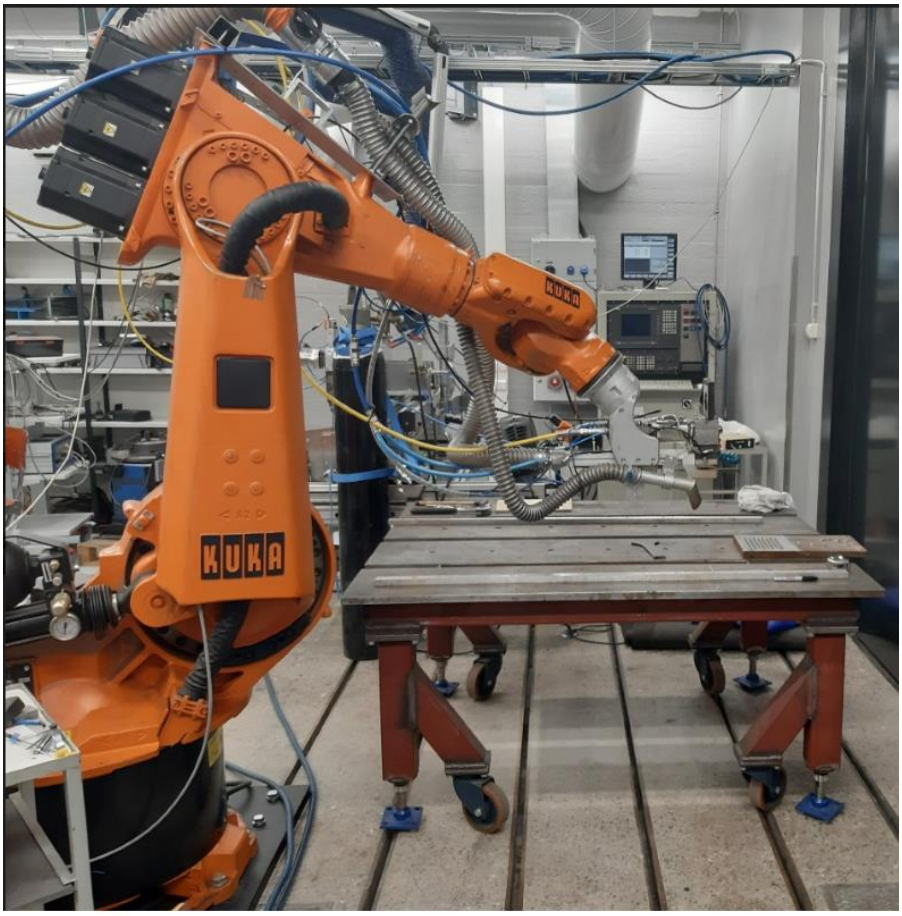


Figure 34: Robot used for laser welding

Likewise, in SAW the test is performed at different angles which are 0°,10°,15° and 20°. To measure the angle, the angle measuring scale which is slant 100 is used as shown in figure below.

Figure 35: Angle measuring scale

The different parameters that were used during the experiment are as shown in the table below.

Table 12: Laser welding parameters

Angles	Power	Welding speed	Focus lens	Fiber diameter	Collimating lens	Focal point
0°	10 kW	60 cm/min	300 mm	400 µm	200 mm	-5 mm
10°	10 kW	60 cm/min	300 mm	400 µm	200 mm	-5 mm
15°	10 kW	60 cm/min	300 mm	400 µm	200 mm	-5 mm
20°	10 kW	60 cm/min	300 mm	400 µm	200 mm	-5 mm

The first experiment is performed when the welding head is perpendicular to the workpiece with the laser power of 10 kW, welding speed of 60 cm/min, fiber diameter of 400 µm and focal point of -5mm. Every other parameter is kept unchanged except angle of incidence. Four different tests are performed with 0°, 10°, 15° and 20°. The angle is changed to verify the research finding from the literature review that the depth of the penetration keeps on decreasing as the angle keeps on increasing from 0 degrees.

The results from the test is shown in figure below.

Figure 36: Final workpiece from laser welding

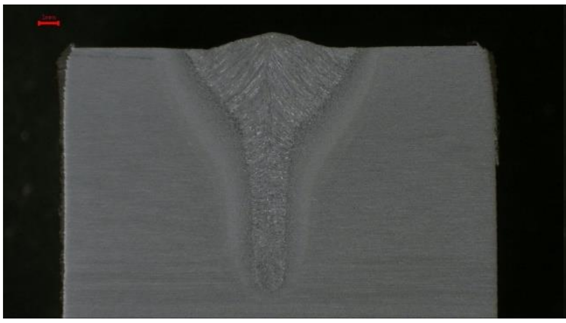
The same procedure is followed as in SAW for obtaining microscopic pictures of the workpieces. The workpieces are grinded, fine grinded and polished just like in SAW. Nital, which is the mixture of nitric acid and alcohol is used for etching. The etching process is shown in the figure below.

Figure 37: Dipping workpiece for 15 seconds

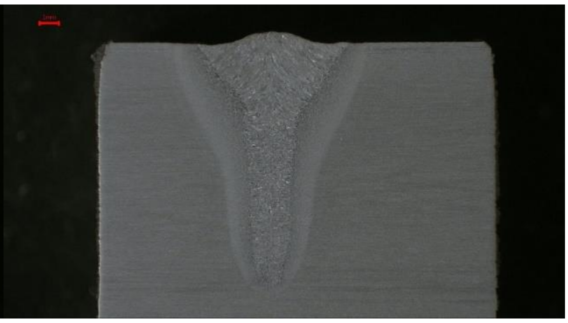
After the etching, the workpieces are washed with clean water and then ethanol is added which is dried afterwards. The etched parts are left on a table for a while and then they are taken to the microscope to have microscopic pictures. The microscope used to take microscopic pictures is shown in figure below.

Figure 38: Microscope used to take microscopic pictures

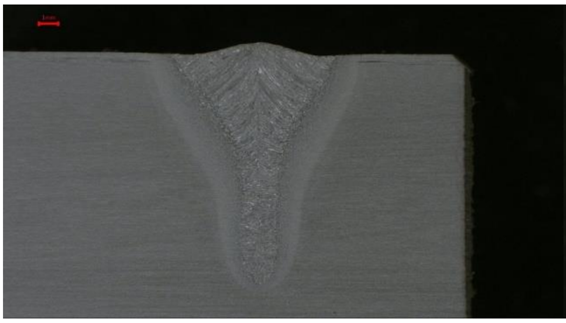
The final pictures from the microscope are as shown in figure below.



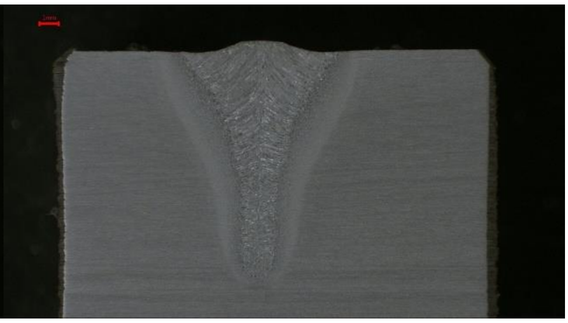
a)



b)



c)



d)

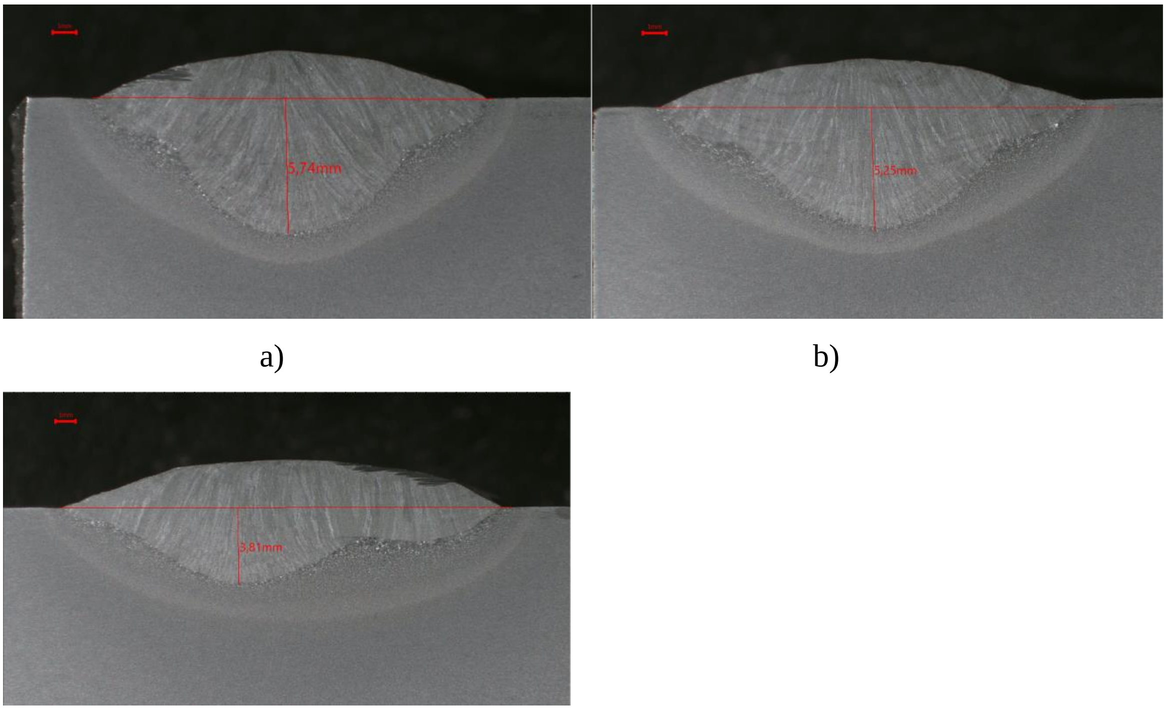
Figure 39: Microscopic pictures a) 0°, b) 10°, c) 15°, d) 20°

4 RESULTS AND ANALYSIS

4.1 Result for Submerged arc welding

4.1.1 Effects of tilting angle on penetration depth

Toupview software is used to measure the depth of penetration and the bead width. The penetration depth and bead width in each angle is shown below.



a) b) c)

Figure 40: Measured penetration depth. a) 0°, b) 10°, c) 20°

The penetration depth at different angle of incidence is as shown in the table below.

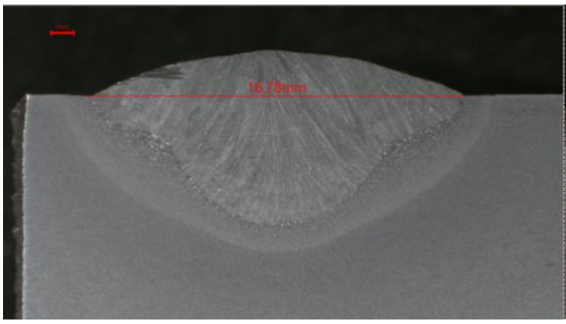
Table 13: Penetration depth in SAW

Angle	Penetration depth
0°	5.74 mm
10°	5.25 mm
20°	3.81 mm

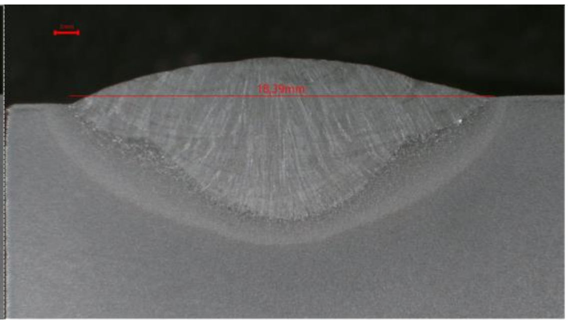
The table shows that the penetration depth at 0°, 10° and 20° are 5.74 mm, 5.25mm and 3.81 mm respectively. The table suggests that the penetration is highest at 0° which is when the welding torch is perpendicular to the workpiece and is lowest at 20°.

4.1.2 Effect of tilting angle on bead width

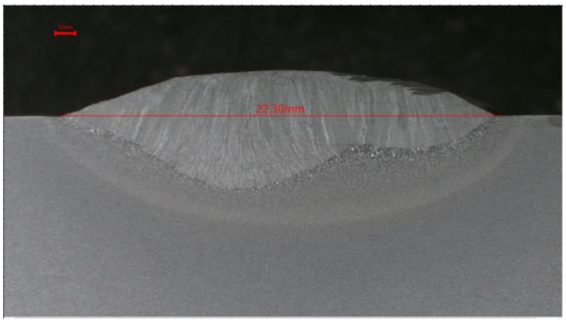
The bead width on the workpiece because of different angles are shown in figure below.



a)



b)



c)

Figure 41: Measured bead width. a) 0°, b) 10°, c) 20°

The bead width at different angle of incidence is as shown in the table below.

Table 14: Bead width in SAW

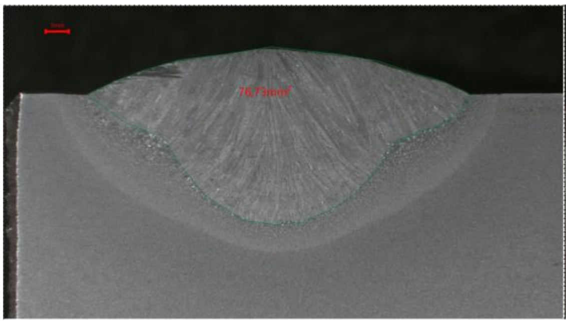
Angle	Bead width
0°	16.78 mm
10°	18.39 mm
20°	22.30 mm

The table shows that the bead width at 0°, 10° and 20° are 16.78 mm, 18.39 mm and 22.30 mm respectively. The table suggests and verify the finding from the literature review [15]

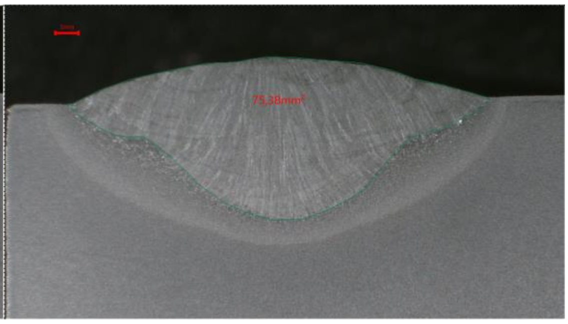
[20] [23] that the bead width is lowest when the welding torch is perpendicular to the workpiece and it keeps on increasing as the angle increases.

4.1.3 Effect of tilting angle on area of welded region

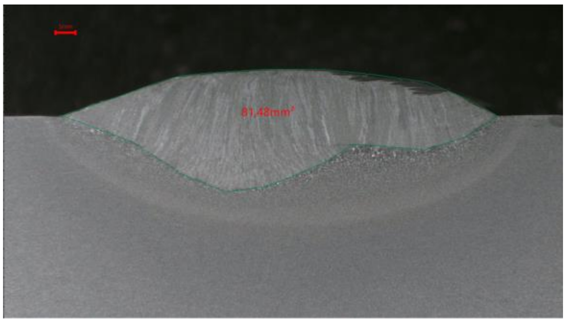
The amount of material deposited at different angles 0°, 10° and 20° are shown in figure below in terms of area of welded region.



a)



b)



c)

Figure 42: Measured area. a) 0°, b) 10°, c) 20°

The area of welded region at different angle of incidence is as shown in the table below.

Table 15: Area welded region in SAW

Angle	Area
0°	76.73 mm^2
10°	75.38 mm^2
20°	81.48 mm^2

The table shows that the area of welded region at 0°, 10°, 20° are 76.73 mm^2, 75.38 mm^2 and 81.48 mm^2 mm respectively. It shows that the area of welded region is decreased at 10° and again increased at 20°. From the literature review it was known that the area of welded region must decrease as the angle increases from 0°. However, as we can see from the figure number 29 the achieved weld at 20° is little bit curvy not straight which is because of fault during the welding. So, it is one of the reasons the area got increased at 20°.

4.2 Analysis of the results of SAW

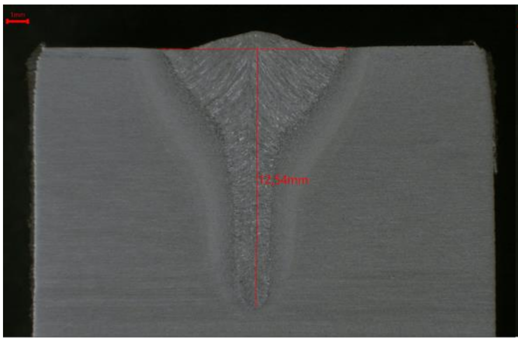
The result of the SAW shows that the maximum penetration is at 0°. As the angle slowly keeps on increasing the depth of penetration keeps on decreasing. This is because in case of pushing angle the base of the metal is not heated unlike pulling [9]. In case of pulling the region to be weld next is already heated so it will help in achieving more penetration as the angle increase. As the figure 21 shows the penetration at pulling angle is more than penetration depth when the welding torch is perpendicular to the workpiece. The same figure also shows that the penetration depth in case of pushing angle is much less than penetration when the welding torch is perpendicular to the workpiece. This is because the welding head in case of pushing angle is at opposite side than weld pool which means that the welding head is moving away from the weld pool. So, the arc has to penetrate the non-heated region of the workpiece as it moves on. Therefore, the penetration depth keeps on decreasing as the angle of incidence keeps on increasing.

The result of the bead width shows that the bead width keeps on increasing as the angle keeps on increasing. The finding from literature review reveals that the bead width keeps on increasing as the angle increases in case of pushing angle. Moreover, angle of incidence is not the only thing on which bead width is dependent. There are other more important factors on which the bead width is directly dependent. As the figure 7-11 shows bead width depends on different factors like welding speed, welding current, voltage, polarity and electrode diameter.

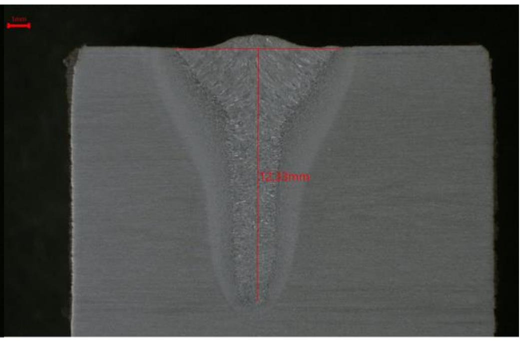
The quality of the weld can be inspected from different ways like visual inspection, X-rays, and ultrasonic. As these welding was done on bead on plate, they were inspected by visual inspection. If the welding was about butt welding, fillet welding then there might be problem of imperfection like underfilling, undercuts, cracks, lack of penetration. These were not the problem on bead on plate welding and there were no pores present on the bead. So, the quality of the welded part was inspected and verified by the laboratory engineer. As per him the quality of the welded part good and acceptable.

4.3 Results for laser welding

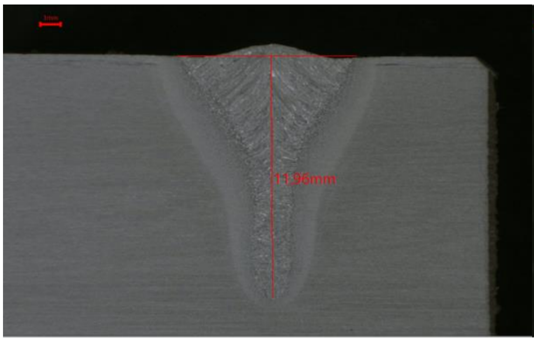
4.3.1 Effect of tilting angle on penetration depth



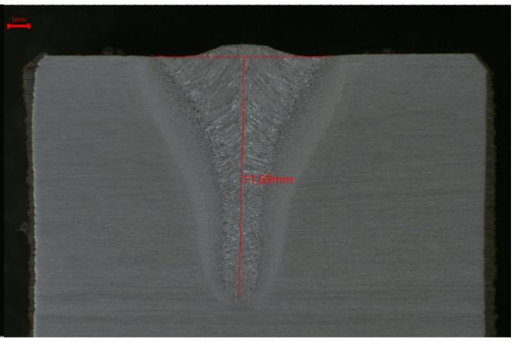
a)



b)



c)



d)

Figure 43: Measured penetration depth. a) 0°, b) 10°, c) 15°, d) 20°

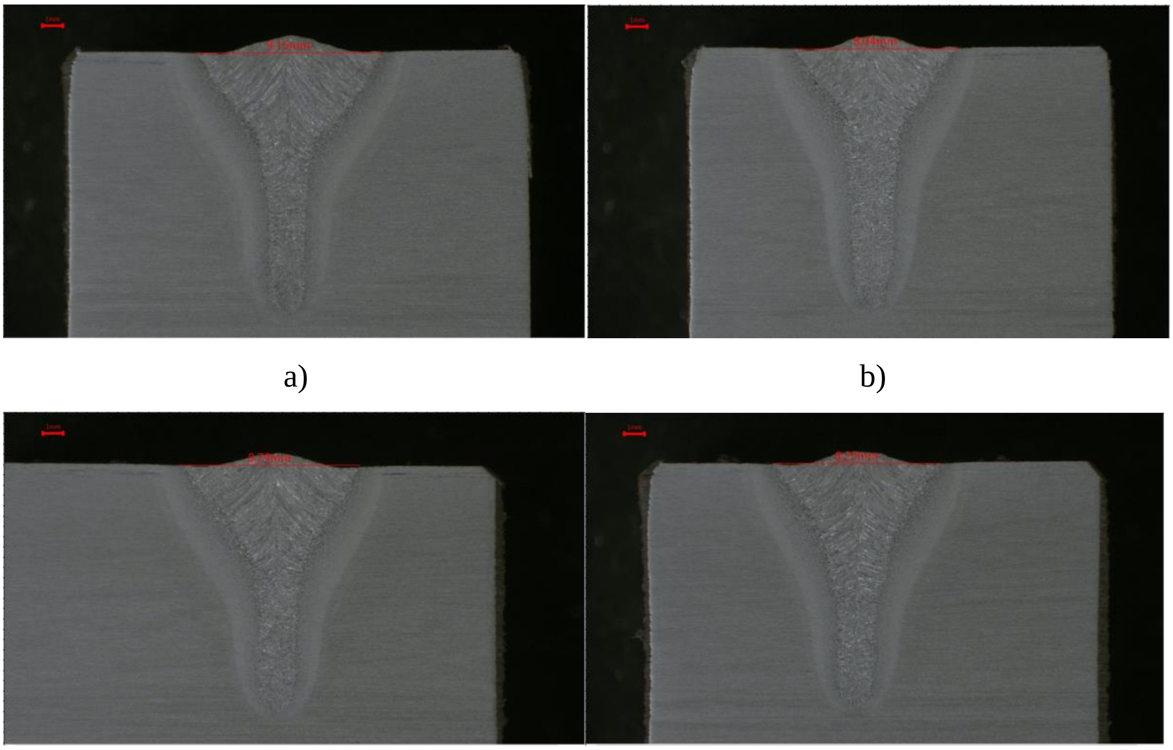
The penetration depth at different angle of incidence is as shown in the table below.

Table 16: Penetration depth in laser welding

Angle	Penetration depth
0°	12.54 mm
10°	12.33 mm
15°	11.96 mm
20°	11.69 mm

The table shows that the penetration depth at 0°, 10°, 15° and 20° are 12.54 mm, 12.33 mm, 11.96 mm and 11.69 mm respectively. The table suggests and verifies the finding from the literature review that the highest penetration is when the welding head is perpendicular to the workpiece. It further verifies that as the angle of incidence is increased then the penetration depth is decreased.

4.3.2 Effect of tilting angle on bead width



a) b) c) d)

Figure 44: Measured bead width. a) 0°, b) 10°, c) 15°, d) 20°

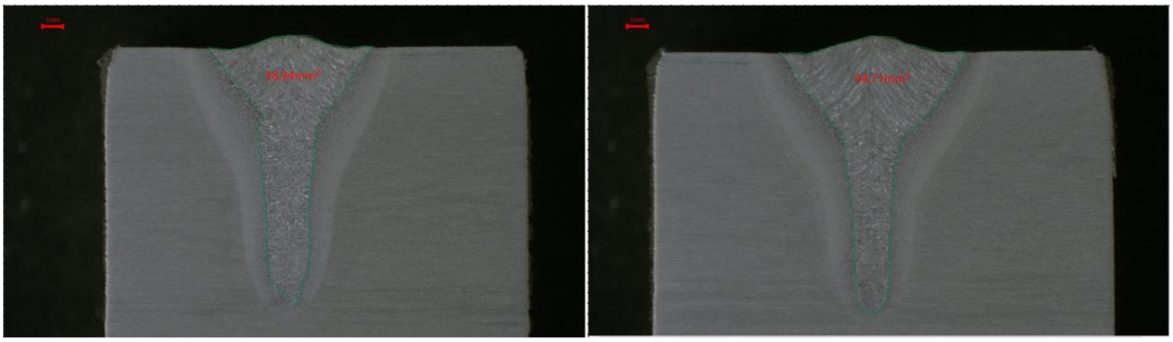
The bead width at different angle of incidence is as shown in the table below.

Table 17: Bead width in laser welding

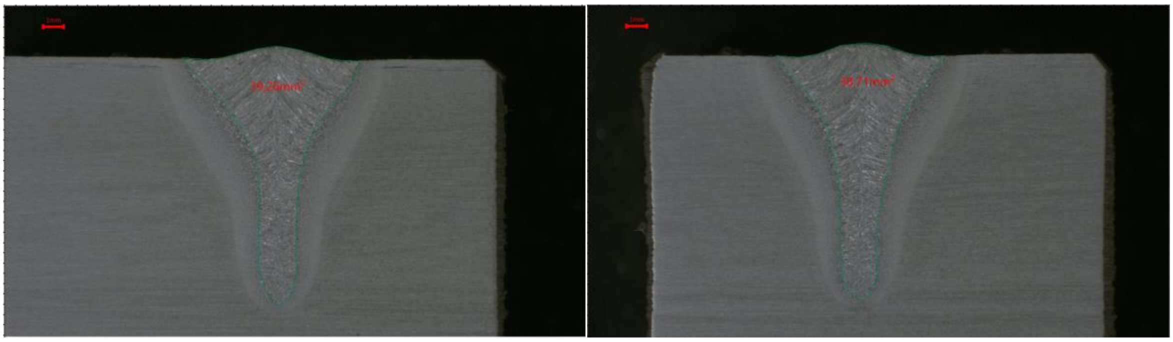
Angle	Bead width
0°	9.15 mm
10°	8.04 mm
15°	8.79 mm
20°	8.25 mm

The table shows that the bead width at 0°, 10°, 15°, 20° are 9.15 mm, 8.04 mm, 8.79 mm and 8.25 mm respectively. Unlike in SAW, no correlation between the angle of incidence and bead width is found from this research.

4.3.3 Effect of tilting angle on area of the welded region



a) b)



c) d)

Figure 45: Area Measured. a) 0°, b) 10°, c) 15°, d) 20°

The area of welded region at different angle of incidence is as shown in the table below.

Table 18: Area welded in laser welding

Angle	Area
0°	38.94 mm^2
10°	44.74 mm^2
15°	39.26 mm^2
20°	38.71 mm^2

The table shows that the area of welded region at 0°, 10°, 15°, 20° are 38.94 mm^2, 44.74 mm^2 and 39.26 mm^2 and 38.71 mm^2 respectively. Unlike in SAW, no correlation between the angle of incidence and area of welded region is found from this research.

4.4 Analysis of results of laser welding

The result of the laser welding shows that the maximum penetration is at 0°. As the angle slowly keeps on increasing the depth of penetration keeps on decreasing. As this method is also called as keyhole welding, when the welding head is perpendicular to the workpiece laser beam will strike straight resulting in deep keyhole. The laser beam cannot have same keyhole as the angle gets increased. Moreover, in pull angle the region to be weld is already heated like in SAW which will also help in increasing penetration depth as the angle of incidence increases.

The figure below presents the finding from the experimental result for both SAW and laser welding. The figure concludes that the effect of angle on penetration depth is very small upto 10° but once it exceeds 10° penetration depth starts decreasing.

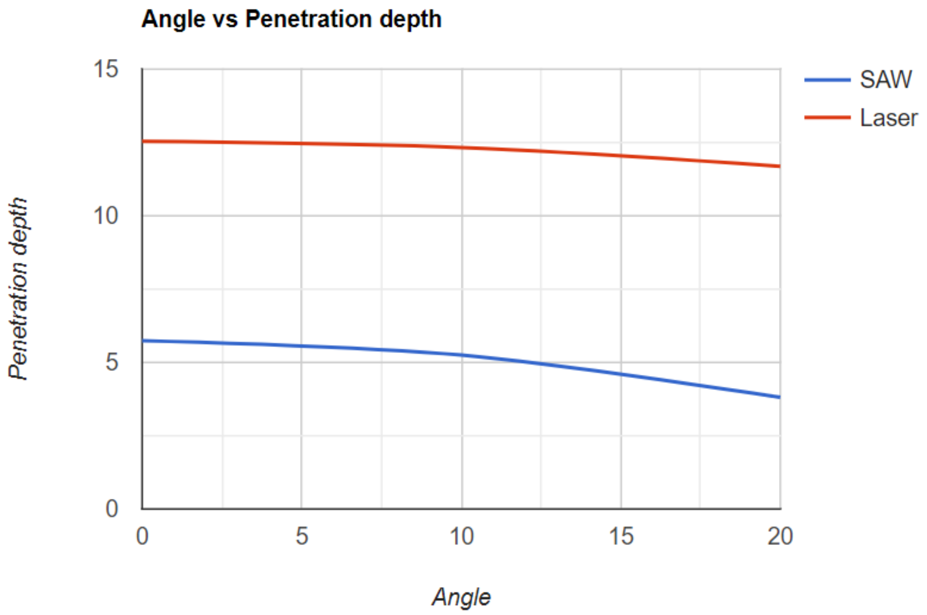


Figure 46: Graph showing Angle vs Penetration depth

When we look at the bead width, it has bead width 9.15 mm, 8.04 mm, 8.79 mm, 8.15 mm at 0°, 10°, 15° and 20 degrees. This experiment does not show any correlation of angle of incidence with the bead width. It may be because all the other parameters like fiber diameter, focal point, focal length were fixed and the only changing parameter was angle of incidence. Probably it will be better to verify in future research about the effect of angle of incidence on bead width by varying fiber diameter, focal point, focal length.

5 CONCLUSION

The effect of angle of incidence on penetration depth is effectively studied in this thesis. Literature review and the experiment are the two methods used in this research. Firstly, some kind of conclusion is drawn from the literature findings and based on that findings the experiment is carried out. Two set of angles of incidence is chosen for the experiment. For SAW the chosen angle of incidence are 0°, 10° and 20° whereas 0°, 10°, 15° and 20° for laser welding. All other parameters like welding speed, power, heat input are not changed throughout the experiment. This research overall presented the effect of tilting angle of incidence angle on penetration depth on SAW and laser welding. As this thesis was a part of laser submerged arc hybrid welding project, the experiment of SAW is done in push angle and laser welding is done in pull angle.

One the first part of the experiment results from the SAW are presented. The results show that the penetration is maximum at 0°. As the angle of incidence is increased, the penetration depth keeps on decreasing while the bead width keeps on increasing with the increasing angle. This was because in push angle the welding torch move away from the molten weld pool which means that the welding torch must penetrate raw non heated region of the workpiece. So, as the angle increase it cannot penetrate the way it penetrated at 0°. This outcome was first drawn from the literature review and later verified from the experiment.

One the second part the experiment results of laser welding are presented. The results reveal that the maximum penetration is at 0°. This was because in pull angle when the welding head is perpendicular to the workpiece laser beam was able to make deep keyhole which will results in deep penetration. As the angle keeps on increasing the molten metal fall on the keyhole and laser beam will not be able to penetrate as it did when the welding head was perpendicular to the workpiece. From the experiment it was also know that there is not significant correlation between angle of incidence and bead width while keeping all other parameter constant.

Another part of the thesis was to inspect the quality of the weld. There are various ways to check the quality of the weld like visual inspection, X-rays, Ultrasonic inspection. X-rays, Ultrasonic inspection are typically done for different kinds of weld like butt weld, fillet weld, T- weld. As our experiment was done on bead on plate, visual inspection was done to verify the quality of the weld. The visual inspection revealed that there were not imperfections present on the bead of the weld. The quality of the weld was verified by the laboratory engineer.

6 FURTHER RESEARCH

There are few questions that are raised during this research which can be the research work for future. As we changed only one parameter which is angle of incidence in this thesis: it will be interesting to see in future by changing other parameters as well like welding speed, welding power, current to check the penetration depth.

The result of the laser welding shows that there is no correlation between angle of incidence and bead width. So, the possible future study could be to check whether the result will be same or different when other parameters are changed.

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AB Bayrock
Svetspulver för pulverbågsvetsning

ST55

CATEGORY	SAW Submerged arc
TYPE	High basic SAW flux with very low hydrogen content
APPLICATIONS	Drilling platforms, crane building, offshore fundamentals, jack ups, narrow gab welding, multi layer welding.
PROPERTIES	Neutral high basic flux suitable for a weight range of wire combinations including multi layer welding in high demanding offshore applications because of its low hydrogen content. Basicity according to Boniszewski: ~3.1 Grain size according DIN EN 760: 2 - 16
CLASSIFICATION	EN ISO 14174: SA FB 1 55 AC(D) H5
SUITABLE FOR	S355, S420, S460, S690, P500, P550, X65, X70, X80, Weldox 700, Naxtra 70, Hardox 400, Dilimax, P91, P24
APPROVALS	DB, LLoyds, DNV, TUV..
WELDING POSITIONS:	

SiO_2+TiO_2	CaO + MgO	Al_2O_3+ MnO	CaF_2	S	P
15	40	20	25	<0.015	<0.015

with Wire	$R_{P0,2}$ (N/mm^2)	Rm (N/mm^2)	A5 (%)	Impact Energy (J) ISO-V -20°C	-40°C	-60°C	Hardness HRc / HV
S3Si*	>460	530-680	>20			>47	
Topcore 742B*	>690	770-940	>17		>80	>69	

* For as welded condition and PWHT 580ºC / 2hr.

REDRYING TEMPERATURE	300-350ºC / 1-2hr
NOTE	Packing: 30 kg sealed metal buckets / 25 kg bags.

Topcore 742B

CATEGORY	SAW Submerged arc
TYPE	High- basicity flux-cored wire for submerged-arc welding.
APPLICATIONS	Crane-, rig, plant-, craft-, lifting and steel construction, pipe work, foundries
PROPERTIES	Remarkable crack resistant weld metal in combination with very low hydrogen content. Therefore, suitable for the economic processing of high-strength and low temperature fine grained structural steels. Excellent welding properties in combination with ST 55 high basic flux even in narrow gabs. Excellent wetting properties compare to solid wires that results in a bigger parameter range and improved deposition rate. To obtain optimum mechanical properties the heat input should be kept below 15 kJ/cm and interpass temperature between 100 and 150ºC.
CLASSIFICATION	AWS A 5.23: F11A8-ECF5-F5 A 5.23M: F76A6-ECF5-F5 EN ISO 26304-A: S 69 6 FB T3Ni2,5CrMo
SUITABLE FOR	StE 690.7 TM, L690M, A 715, StE 690 V, S690QL, A 709, A 515, A 517, EStE 690 VA, S690G1QL1, A 514, A 633, A 709 Naxtra 70, Weldox 700, Dilimax, S620Ql1, S690QL1, S600MC, S700MC, Naxtra 63, Naxtra 70, TStE620, TStE690, Weldox 500, Weldox 700, Hardox, L480 - L550, X65 - X80, Hardox 400, XAR 400, Dilidur 400, 20MnCr65, 28CrMn43
APPROVALS	LLoyds (5Y69), ABS (5Y69), DNV, TUV, BV, CE approved

WELDING POSITIONS:

WELD DEPOSIT ANALYSIS WITH ST55 (WEIGHT %)

C	Mn	Si	Cr	Ni	Mo	P	S
0.08	1,6	0,4	0,5	2,2	0,5	<0.015	<0.015

Heat Treatment	$R_{P0,2}$ (N/mm^2)	Rm (N/mm^2)	A5 (%)	Impact Energy (J) ISO-V -20°C	-40°C	-60°C	Hardness HRc / HV
AW	>690	770-900	>17		>80	>69	

AW: as welded

Welding Parameters			Packing		
D (mm)	Voltage (V)	Current (A) DC+	spool type	kg / spool / drum	kg / pallet
2,0	28-34	180-320	K-415 / Drum	25 / 300	
2,4	28-38	250-500	K-415 / Drum	25 / 300	
3,2	28-40	400-800	K-415 / Drum	25 / 300	
4,0	28-40	500-900	K-415 / Drum	25 / 300	

REDRYING TEMPERATURE Not required

DILLIMAX 500 ML

FINE GRAINED HIGH STRENGTH TMCP STEEL PLATES

Specification DH-E77-D
Edition: November 2009

DILLIMAX 500 ML is a thermomechanically rolled, fine-grained structural steel. It is characterized by high toughness and strength combined with a lean chemistry. Due to its chemical composition, this material has a low carbon equivalent and hence excellent fabrication properties, particularly weldability. The steel is preferentially used by the customers for sophisticated design in constructional steelwork, hydraulic steelwork, mechanical engineering, offshore constructions, storage tanks or spheres.

Product description

Designation and range of application

DILLIMAX 500 ML is usually delivered with minimum tested impacted values at -50 °C. Other testing temperatures can be agreed upon request.
DILLIMAX 500 ML can be delivered in thickness from 10 to 75 mm in accordance with our dimensional programme for TMCP rolled steel. Other thicknesses are possible on request.

Chemical composition

For the ladle analysis the following limiting values are applicable (in %):

C	Si	Mn	P	S	Al	Ni	Cu	Mo	Cr	V	Nb	Ti
≤ 0,09	0.15-0.55	1.00-1.75	≤ 0.020	≤ 0.005	≥ 0.02	≤ 0.70	≤ 0.35	≤ 0.35	≤ 0.35	≤ 0.08	≤ 0.05	≤ 0.025

Maximum carbon equivalent:

Plate Thickness t [mm]	CEV_1 1)	CEV_2 2)	CET 3)	Pcm 4)
$t \leq 50$	0.45	0.47	0.30	0.24
$50 < t \leq 75$	0.47	0.49	0.31	0.24

Auxiliary data:

	20 mm	60 mm
C	0.08	0.08
CEV_1	0.43	0.44
CEV_2	0.44	0.45
CET	0.28	0.28
Pcm	0.21	0.21

Delivery Condition

Thermomechanically rolled (short designation M) 5)

1) $CEV_1 = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14$
2) $CEV_2 = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$

Mechanical and technological properties in the delivery condition

Tensile test at ambient temperature - transverse test specimens in accordance with EN 10025 -

Plate Thickness t [mm]	Minimum Yield Strength [1)] R_{eH} [MPa]	Tensile Strength R_m [MPa]	Minimum Elongation A5 [%]
$t \leq 16$	500	610 - 750	17
$16 < t \leq 50$	490	610 - 750	17
$50 < t \leq 75$	480	600 - 750	17

Impact test on Charpy-V-specimens - longitudinal test specimens -

	Test Temperature [°C]	Impact Values A_v [J]
DILLIMAX 500 ML	-50	30

Other testing temperatures can be agreed upon request.
The specified minimum value is the average of 3 tests. Not more than one individual value is permitted to be below this minimum value; it has to be at least 70 % of this minimum average value. Subsize specimens are admitted for plate thickness ≤ 12 mm, the minimum specimen width is 5 mm. The minimum impact energy will be decreased proportionally.

Option:

As an option, the mechanical values can be adapted to the values standardised for S500Q in EN 10025-6 such as for the yield strength $R_{eH} \geq 500$ MPa for $t \leq 50$ mm and $R_{eH} \geq 480$ MPa for $50 < t \leq 75$ mm and for the tensile strength R_m = 590 - 770 MPa.

Testing

Tensile test and impact tests are carried out once per heat, 40 t and thickness range as specified for the yield strength according to above table. Tests on every plate-as-rolled may be possible on request.
The specimens for the tensile test are prepared according to EN 10025-4. Testing is carried out in accordance with EN 10002-1 on specimens of gauge length $L_0 = 5.65 \sqrt{S_0}$ or $L_0 = 5d_0$.
Unless otherwise agreed, the impact test will be performed according to EN 10045-1 at a temperature of -50 °C on Charpy-V longitudinal test specimens taken as follows:

- for plate thickness < 40 mm: close to the surface
- for plate thickness ≥ 40 mm: $^1/_4$ of the plate thickness

An optional bend test on transverse specimens with a bending angle of 180° at a diameter of mandrel ≥ 3.0 x specimen thickness can be ordered.
Unless otherwise agreed, the test results are documented in a certificate 3.1 in accordance with EN 10204.

Identification of plates

Unless otherwise agreed, the marking is carried out with low stress steel stamps with at least the following information:

- steel grade (DILLIMAX 500 ML)
- heat number
- number of mother plate and individual plate
- the manufacturer's symbol
- authorized inspection representative's sign

Processing

The entire processing and application techniques are of fundamental importance to the reliability of the products made from this steel. The user should ensure that his design, construction and processing methods are aligned with the material, correspond to the state-of-the-art that the fabricator has to comply with and are suitable for the intended use. The customer is responsible for the selection of the material.