OPTIMIZATION OF FCAW AND GMAW BY USING RSM AND CCD WITH TAGUCHI QUALITY LOSS FUNCTION AND DESIRABILITY FUNCTION

BY

KASHIF NAZIR

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This thesis, written by **KASHIF NAZIR** under the direction his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfilment of the requirements for the degree of **Master of Science in Mechanical Engineering.**

Thesis Committee

Anwar Khalil Sheikh

Dr. Anwar Kahlil Sheikh
(Advisor)

Dr. Abu-Dheir, Numan
(Member)

Dr. Sulaman Pashah
(Member)

Dr. Zuhair Mattoug Gasem

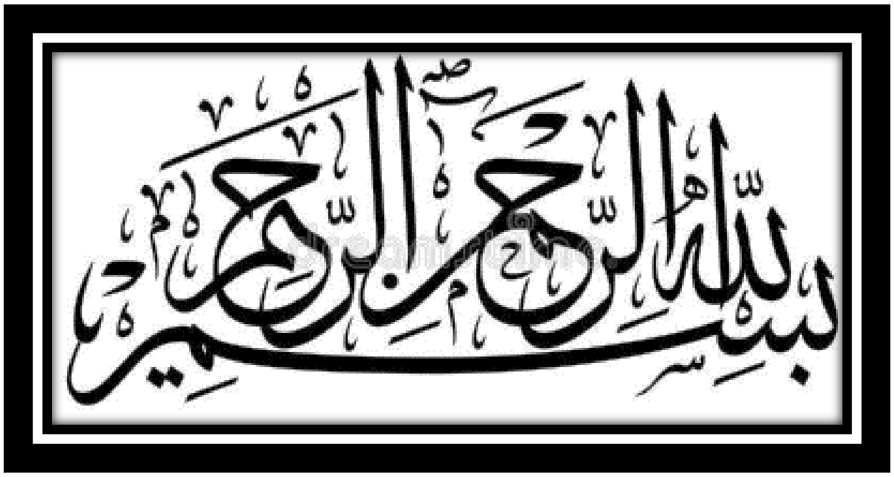
Department Chairman

Dr. Salam A. Zummo
Dean of Graduate Studies

عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES

28/5/19

Date



Dedicated to My Beloved Father (late), Mother and
Teachers whose constant prayers, sacrifice and inspiration led to this beautiful accomplishment

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First and foremost, all admiration is due to Allah subhana-was-ta'ala for bestowing me with health, knowledge and patience to complete this work. The Almighty, who alone made this accomplishment possible. I seek His mercy, favour and forgiveness.

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LIST OF ABBREVIATIONS

FCAW	:	Flux-Core Arc Welding
GMAW	:	Gas Metal Arc Welding
DOE	:	Design of Experiment
RSM	:	Response Surface Method
CCD	:	Cubic Composite Design
Q	:	Total Heat Input in System (KJ/mm)
T	:	Travel Speed (mm)
α	:	Confident Level
R1, R2, R3, R4	:	Welding Responses
F1, F2, F3, F4	:	Welding Controllable Factors
ANOVA	:	Variance Analysis
CCD	:	Cube Composite Design
RSM	:	Response Surface Methodology
USL	:	Upper specifications Limit
LSL	:	Lower Specifications Limit
CE	:	Carbon Equivalent
HI	:	Heat In-Put
P-value	:	Probability at confident level
S/N	:	Signal-to-Noise Ratio
L-Type	:	Larger-the-Best
S-Type	:	Smaller the Best

N-type	:	Nominal the Best
ESV	:	Welding Essential variables
SEV	:	Welding Supplementary Essential Variables
NEV	:	Welding Non-Essential variables
D	:	Composite Desirability function
di	:	Individual Desirability
CTWD	:	Contact tube to work distance
WPS	:	Welding Procedure Specification
PQR	:	Procedure Qualification Record
ASME	:	American society of mechanical Engineer
DPT	:	Dye Penetrant Testing
RT	:	Radiographic Testing
SQRT	:	Square Root
Sq.	:	Square

ABSTRACT

Full Name : Kashif Nazir

Thesis Title : Optimization Of FCAW/GMAW By Using Response Surface Methodology and Cube Composite Design Along with Taguchi Quality Loss Function and Desirability Function

Major Field : Master of Science in Mechanical Engineering

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Semi-automatic conventional welding processes such as FCAW and GMAW are increasingly being utilised in many fabrication and manufacturing industries due to high production rate and ease of work in windy outdoor condition. This study is performed to find out the enhanced quality weld conditions by narrowing down the tolerance window to generate superior weld which satisfies the criteria of the weld with nominal bead width, highest tensile strength, nominal hardness and minimal discontinuities numbers.

The sum of all the above features will define the enhanced quality and productivity of the weld because quality of welds is the level of perfection that welds exhibit about the whole volume of weldment as well as to the profile of weld surface appearance. Enhanced quality weld related high productivity due to optimum blend of parameters which inevitably develop minimum or no defect .

Data were collected as per response surface methodology, and variance analyses were performed to find the relationship between weld factors and responses. Linear regression and multiple object optimisation approaches were made to determine weld parameters with enhanced output through desirability function.

Visual inspection, dye penetrant testing, macrography, chemical analysis, hardness testing and micrography have been conducted to detect surface and sub-surface defects of test coupons made of ASME group "P1" carbon steel material A572 and A36. Butt welded joints have been made by using several levels of current, heat input, voltage and travel speed.

Quality of produced welds has been evaluated in terms of hardness value, penetration index, spatter index, deposition rate and reinforcement height. The optimal surface region found at 72% composite desirability having centred values for FCAW as wire feed at 266 mm/min, heat input at 23kj, current at 216A and CTWD at 12mm. GMAW Optimal surface region found at 78% composite desirability having centred values as voltage 33.2V, wire feed 102mm/min and welding speed at 50cm/min.

The optimised values obtained from these techniques were compared with experimental results and found a comparison error of less than 2%. The above RSM region around composite desirability values of FCAW and GMAW are the obtained framework for achieving enhanced quality weld.

ملخص الرسالة

الاسم الكامل: كاشف نذير

عنوان الرسالة: تحسين عمليات اللحام التي تقوم بها FCAW و GMAW وتحقيق التميز في الجودة

التخصص: ماجستير العلوم في الهندسة الميكانيكية

تاريخ الدرجة العلمية: أبريل 2019

يتم استخدام عمليات اللحام التقليدية شبه الآلية مثل FCAW و GMAW بشكل متزايد في العديد من الصناعات التحويلية والصناعية بسبب ارتفاع معدل الإنتاج وسهولة العمل في حالة الهواء الطلق العاصفة. يتم إجراء هذه الدراسة لمعرفة ظروف اللحام المحسنة الجودة من خلال تضييق نافذة التسامح لتوليد لحام متفوق يفي بمعايير اللحام بعرض الخرزة الاسمي وأعلى قوة شد وصلابة اسمية وأقل عدد من حالات التوقف.

سيحدد مجموع جميع الميزات المذكورة أعلاه الجودة والإنتاجية المحسنة للحام لأن جودة اللحامات هي مستوى الكمال الذي تظهره اللحامات حول الحجم الكامل للحام وكذلك المظهر الجانبي لمظهر سطح اللحام. جودة محسّنة ذات صلة بالحام عالية الإنتاجية نظرًا للمزيج الأمثل للمعلمات التي تؤدي حتماً إلى تطوير عيب أدنى أو بلا عيب.
تم جمع البيانات حسب منهجية سطح الاستجابة ، وأجريت تحليلات التباين لإيجاد العلاقة بين عوامل اللحام والاستجابات. تم إجراء الانحدار الخطي وطرق تحسين الكائن متعددة لتحديد معلمات اللحام مع الإخراج المحسن من خلال وظيفة مرغوب فيه.

تم إجراء الفحص البصري ، واختبار اختراق الأصباغ ، والتحليل الكيميائي ، والتحليل الكيميائي ، واختبار الصلابة ، والكشف الدقيق عن العيوب السطحية وشبه السطحية لكوبونات الاختبار المصنوعة من مواد الفولاذ الكربوني ASME A572 "P1" و A36. تم عمل الوصلات الملحومة بعقب باستخدام عدة مستويات من التيار ، والمدخلات الحرارية ،

والجهد وسرعة السفر. تم تقييم جودة اللحامات المنتجة من حيث قيمة الصلابة ، مؤشر الاختراق ، مؤشر الترشيش ، معدل الترسيب وارتفاع التسليح. المنطقة السطحية المثالية التي توجد عند 72٪ من الرغبة المركبة لها قيم مركزية لـ FCAW كتغذية سلكية تبلغ 266 ملم / دقيقة ، ومدخلات الحرارة عند 23 كيلو جول ، الحالية عند A216 و CTWD عند 12 ملم. تم العثور على منطقة سطح مثالية من GMAW عند 78٪ من الرغبة المركزة التي لها قيم مركزية مثل الجهد 33.2 فولت وتغذية الأسلاك 102 ملم / دقيقة وسرعة اللحام عند 50 سم / دقيقة.

وتمت مقارنة القيم المحسنة التي تم الحصول عليها من هذه التقنيات مع النتائج التجريبية ، ووجد خطأ مقارنة أقل من 2 ٪. إن منطقة RSM المذكورة أعلاه حول قيم الرغبة المركبة من FCAW و GMAW هي الإطار الذي تم الحصول عليه لتحقيق جودة لحام أفضل.

CHAPTER 1

INTRODUCTION OF THESIS

Losses to society in term of life and property due to the catastrophic failure of pressure parts often traced to defective welds. To overcome defects, a high degree welding codes and standards have evolved. Significant advances and researches are done in welding science and technology in recent years where researchers and scientists have focused mostly on welding works which were executed in the welding laboratory and often it is not clear that whether a certified welder has done background experiments used in these studies. We did the studied on the GMAW/FCAW welding processes which used for welding in a remote area such as welding in the windy and dusty environment for cross country pipelines where the arrangement of welding shop is not economically feasible. Moreover, we had used only ASME section ix certified welders and welding procedure specification (WPS) for throughout the thesis.

The driving force of the thesis is the voices of fabricators, manufacture and contractors who consistently report that their welding issues are the need to reduce the welding costs due to rework of defects welds and to improve the welding productivity about project completion schedule. To overcome the contractor's field issues related to welding quality, many international companies such as Saudi Aramco, British petroleum have narrow down the tolerance window as provided by international standards such as ASME, AWS and API. Therefore due to having international welding certification and vast field welding experience, we considered the FCAW and GMAW are the best-suited welding processes. However, these processes need to be further optimised for the project specification condition parameters to maximise the welding features because such optimisation of the welding process will affect both welding cost and welding productivity.

1.1 INTRODUCTION TO WELDING PROCESSES USED

Since we had used semiautomatic welding processes for the thesis study, therefore subsequent section will give a brief introduction to GMAW and FCAW.

1.1.1.INTRODUCTION TO GMAW

In gas metal, arc welding materials are melted and joined by heating them by an arc which produced between filler wire which continuously fed and the metals. Arc is protected and shielded by using inert gases like helium and argon. That is why GMAW is also called metal inert gas process (MIG). GMAW is a constant voltage process, and DCEP used in GMAW. GMAW line diagram depicted in Figure 1 (courtesy of ASM welding handbook vol. 6) [1].

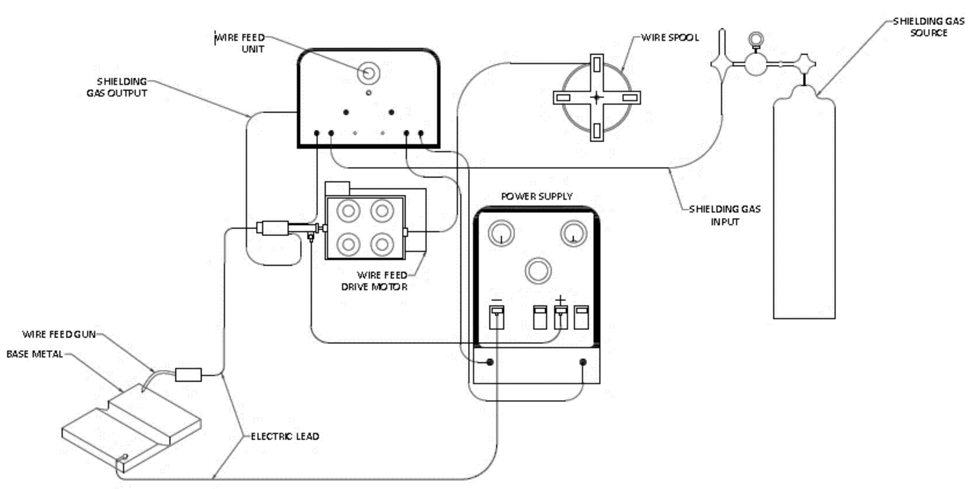


Figure 1: Schematic diagram of the GMAW process

1.1.2. INTRODUCTION TO FCAW

Flux-core arc welding (FCAW) is very similar to GMAW in the process, but the difference is that here flux cored wire is used instead of a solid wire. Flux cored wire is a metal tube where the flux is enfolded inside it and like covering electrodes in SMAW in a way to protect the molten metal from external effects. In FCAW additionally, use shielding gas is optional. The FCAW process flow shown in Figure 2 (Courtesy of ASM Welding Handbook Vol. 6) [1]

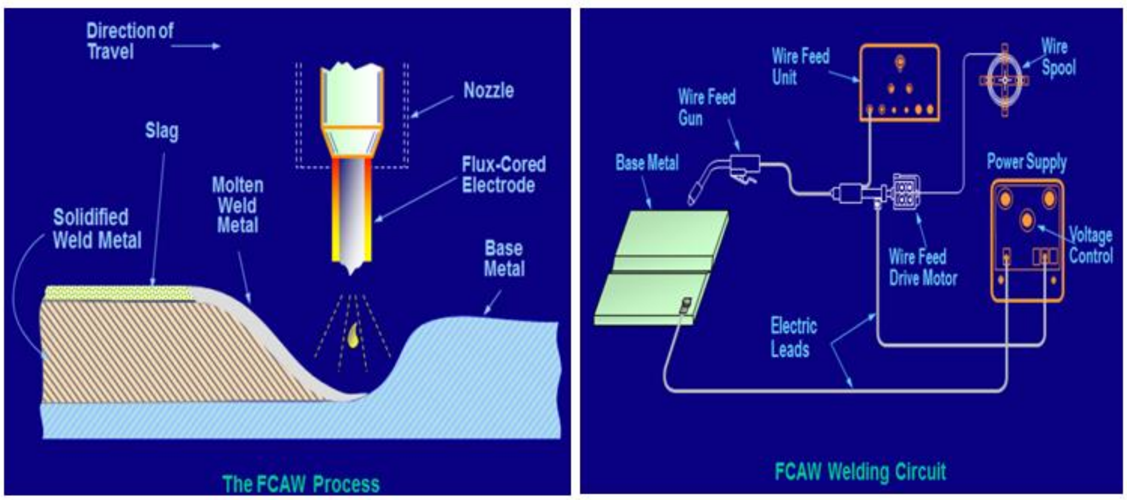


Figure 2: FCAW process flow and welding circuit

The FCAW process utilises semiautomatic, mechanised, and fully automatic welding systems. The essential equipment includes a power supply, the wire feed system, and a welding gun. The required auxiliary equipment, such as shielding gas, depends on the process variant used and the degree of automation. Fume removal equipment must also consider in most applications of the FCAW process. The equipment used in the gas-shielded FCAW process is typically identical to GMAW equipment. The recommended power supply for the semi-automatic FCAW process is a constant-voltage direct current (dc) machine. Process philosophy of FCAW process is depicted in Figure 2. Most power supplies used for semiautomatic FCAW have output ratings of 600 A or less. A power supply of 60% or more rating of the duty cycle is the best choice for most industrial applications, whereas a duty-cycle rating as low as 20% may be enough for maintenance and repair applications. Constant-current power supplies used in certain situations, such as field welding applications, where portable constant-current SMAW power supplies are readily available. The addition of a contactor and a voltage-sensing wire feeder makes this an adequate welding system. However, such a system recommended when the use of a constant voltage system is not feasible because constant-current systems produce an inherently less-stable welding arc than constant-voltage systems. Wire feeders for constant-voltage FCAW systems are generally simple devices that provide a constant wire feed speed. The power supply provides enough current to maintain an arc at the voltage that is present at the power supply. A change in wire feed speed results in a change in the welding current. [2]

In a constant-current system, the wire feeder is somewhat more complicated. The welding current is preset at the power supply. The wire feeder has a voltage-sensing feedback loop that allows it to adjust the wire feed speed to maintain the desired welding voltage. The wire feeder generally contains systems to close the contactor and open the shielding gas solenoid valve (gas-shielded FCAW process only) when welding started. Because flux-cored wires easily deformed by excessive feed roll pressure, knurled feed rolls used in the FCAW process. Some wire feeders use a single drive roll paired with an undriven pressure roll. Others have one or two pairs of drive rolls. It generally believed that systems having two pairs of drive rolls require the least drive roll pressure to provide dependable feeding.

Both air-cooled and water-cooled welding guns used in the semiautomatic FCAW process. Air-cooled guns are generally preferred because they are simpler to maintain, lighter in weight, and less bulky. Water-cooled guns may be required when welding currents over 500A used, especially when the shielding gas is rich in argon [1] [2].

1.2 DEFINING WELD QUALITY AND PRODUCTIVITY RELATIONSHIP

Quality of welds defined as "the level of perfection that welds exhibit about the entire volume of weldment as well as to the profile of weld surface appearance". The study will perform to find out the best (enhanced quality) welding condition whereas the resulting best (superior) weld is the weld with hardness value as nominal the best, tensile strength value with "larger the best", bead width value "nominal the best", discontinuities number per weld's count value "smaller the best".

Productivity in term of quality defined as an optimum blend of parameters which inevitably develop minimum or no defect then the process will result in high productivity. Discontinuities such as burn through, weld spatter, undercut, lack of fusion and lack of penetration observed in FCAW/GMAW. Discontinuities occur due to either low craft or due to the inappropriate setting of welding parameter such as current, voltage, travel speed. in this study, effects due to low craft will not consider because the all the welds will be welded by well experienced and qualified welders according to welding standards.

1.3 THE MOTIVATION OF STUDY

The author has observed that all previous optimisation study had done on the controlled workshop of FCAW/GMAW by using analysis tools such as grey analysis, regression analysis, genetic algorithm or artificial neural network methodology. Auditor tried to study welding data generated from real-time welding environment such as windy, dusty and constraint working-space with response surface methodology. Optimisation of the welding process is done to enhance the quality of weld because the quality of weld has an ultimate effect on the following;

1. Analysis of the actual cost of welding by segregating the significant variables from non-significant welding variables.
2. To minimise the welding rework, rejection and scrap rate.
3. To minimise or eliminate the post-welding grinding for unwanted spatter and excess weld metal
4. To minimise the wasted time due to unnecessary motions

1.4 SOURCE OF DATA

The study conducted in this thesis is data dependent, and data should be reliable and by the requirements of the design of experiments generated matrix. We will primarily use field data complemented with some additional data generated to fulfil the needs of design of experiment strategy adopted.

1. Field study experiments result under consistence environments process parameters of doe (unpublished data) welded by ASME section ix certified welders on certified ASME section ix welding procedure qualification (WPS).
2. Additional data generated corresponding to the missing conditions as specified in the doe experimental design matrix.

1.5 OBJECTIVE OF THESIS

The main objective of this research is to develop a framework of maximising the quality of the weld by deploying design of experiments strategies and analyse the results to determine the robust parameters combination for highest desirable weld (using desirability function) or a weld which causes the minimum loss to the society. Within the ordinarily acceptable range of weld features from the international standard, we will further narrow down the specific weld features to enhance the weld quality to its highest level. We will primarily be focusing on collecting the field data from real-time welding environment on ASTM A572 Gr. Fifty types I and ASTM A36/53 materials.

1.6 METHODOLOGY

To achieve these objectives, we will be doing the following:

1. Full factorial design formation for all parameters of FCAW/GMAW welding
2. Identify significant factors by performing an analysis of variance.
3. Find out upper 95% limits and lower 95 % limits based on the confident level (alpha=5%),
4. Find the optimised desirability function for only significant controllable factors.
5. Validate the results of by welding a test specimen for each case at optimised conditions.

The detail optimisation process discussed in chapters 4 and 5.

1.8 THESIS CHAPTER ORGANIZATION AND PURPOSE

The thesis organised into chapters such as in chapter 2, physics of welding and mathematical fundamental, where we have discussed significant physics and some

Equations which will be used in chapter 6 for the conclusion and result in the discussion. Chapter 3 will discuss the significant issues in welding as highlighted by engineering contractor along with the latest published literature review. Chapter 4 and five will discuss the design of experiment philosophy for the GMAW/FCAW respectively. Chapter 6 will discuss the result and conclusion along with the recommendations.

CHAPTER 2

PHYSICS OF WELDING AND MATHEMATICAL FUNDAMENTAL

Chapter two discussed the physics of weldings such as heat transfer, the power density of welding process influences on welding quality and mathematical expression for carbon equivalent and welding indexes such as porosity, concavity and spatter.

2.1 ENERGY SOURCE INTENSITY

Before the discussion on power density, the following are the data specific data obtained for welding processes, i.e. GMAW/FCAW used in the thesis. The data source reference from ASM welding handbook volume 6 [1];

1. Power density of GMAW/FCAW = >10 kW/cm^2
2. Based on power density expected HA length = 0.5 cm
3. Interaction time to melt the carbon steel = 0.8 sec

Power density expressed in watt per square centimetre. It means it is the electric power over the unit area is called power density; the increase of power density is required to create the weld pool. The relation to power density to heat input is mentioned in Equation 1(courtesy of ASM welding handbook vol 6) [1].

$$\text{Power density} \quad \alpha \quad 1/\text{ Heat input} \qquad (1)$$

Therefore, engineer intend is to increase the power density so that heat input can decrease due to which distortion and weakening of workpiece can control. In addition to decreasing the heat input, increase of power density is used to have deeper weld penetration, higher welding speeds and less damage to parent metals. Different welding process has different power density, and power density plays a vital role in the selection of appropriate welding process. the same discussion is accumulated below in a graphic

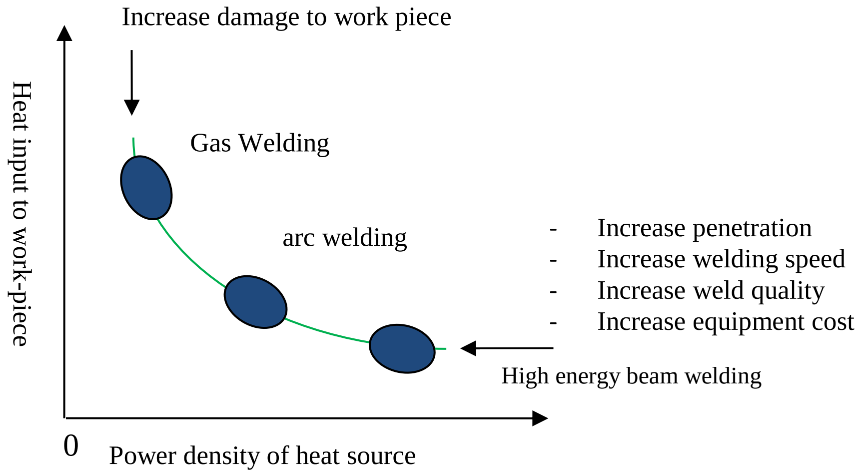


Figure 3: Comparison of heat input requirements about power density

Figure 3 (courtesy of ASM welding handbook vol 6 [1]) is the comparison between different welding processes about power density and heat input. Power density is the measuring scale of heat intensity or concentration, more heat intensity or more heat concentration on the outside area, the smoother melt. If heat intensities increase up to 10^6 or 10^7 w/cm^{2,} then most of the metal will vaporise within a few microseconds. Therefore, there is a limit to increasing the power density of the welding process; especially for heat intensity shall not be more than 10^6 w/cm^2. Power density spectrum has been developed in Figure 4 to illustrate the concept taken from ASM welding handbook volume 6 [1].

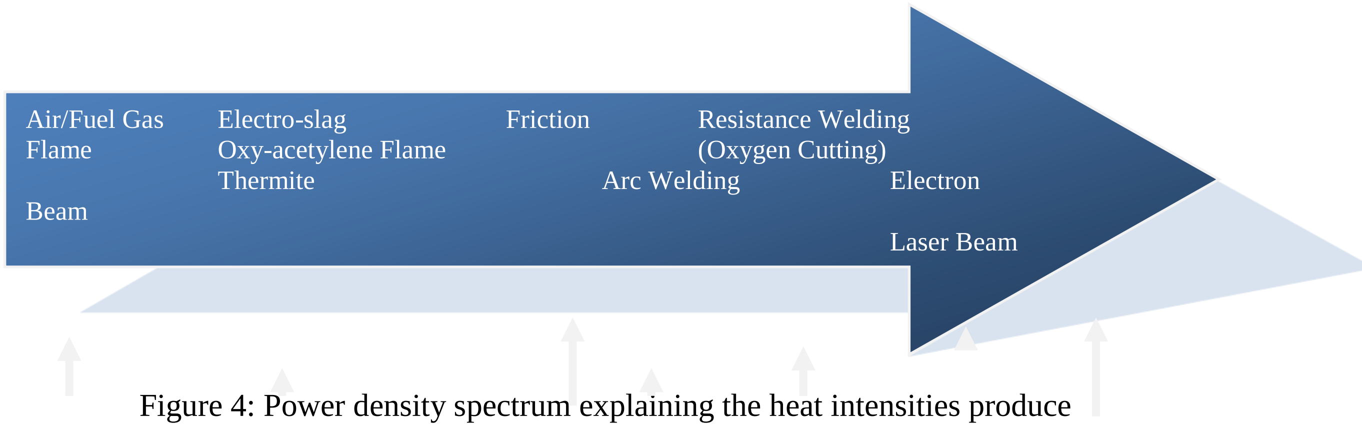


Figure 4: Power density spectrum explaining the heat intensities produce

From power density, it can see that for fusion welding; the power density shall be between 0.001 to 1m w/cm^2. By Einstein Equation as given below, we can explain that power density of welding process is inversely proportional to the interaction time of heat source for all materials as referenced in Equation 2 (courtesy of welding metallurgy by the Sindo [2]).

$$X \sim \sqrt{\alpha t} \tag{2}$$

Where;

X = distance about which heat diffuses (cm)

α = thermal diffusivity of material (cm2/s)

t = time (sec.)

Since higher power density of heat source will produce enough weld pool which is impossible to control by a human manually such as in electron beam welding, therefore for the training of welder it is recommended to start with the oxy-acetylene process so that welder can easily enquire skill how to control weld pool by getting enough time.

Following are the parameters which are related to power densities;

1. The spot size of heat on the workpiece
2. Heat affected zone
3. Depth-to-width ration of the weld pool

Power density can be changed either by changing equipment rating or by changing spot size, changing the rating of welding equipment is expensive therefore spot size can be adjusted as required because of the decrease in spot size results in a squared increase in heat intensities. [2]

The width of the heat affected zone (HAZ) is also related to power density. HAZ width is related to process interaction time and thermal diffusivity of solid and in case of low power densities, HAZ width change due to interaction time whereas in other of the higher power density of welding process HAZ width is not depended on interaction time of heat source with the workpiece.

Figure 5 (courtesy of welding metallurgy by Sindo [2]) shown the maximum power density capability of the different welding process. Power densities control heat intensities, and heat intensities control depth and width of the weld pool and weld pool depth-to-width ration can vary between 0.1 inches to 10-inch base on applied heat intensities. Therefore, the selection of the welding process is crucial because all welding process have different capabilities to power densities. Below is a display of the welding process about power densities. With reference, all above explanation, too much low power density due to lack of penetration, weak fusion and too much high-power densities due to damage to the parent metal, distortion in joint, softening of HAZ, reduction in mechanical properties, are not favourable for the welding process. Therefore, for sound weld optimal value to power densities to be calculated for the selected process and the design of the experiment can do it.

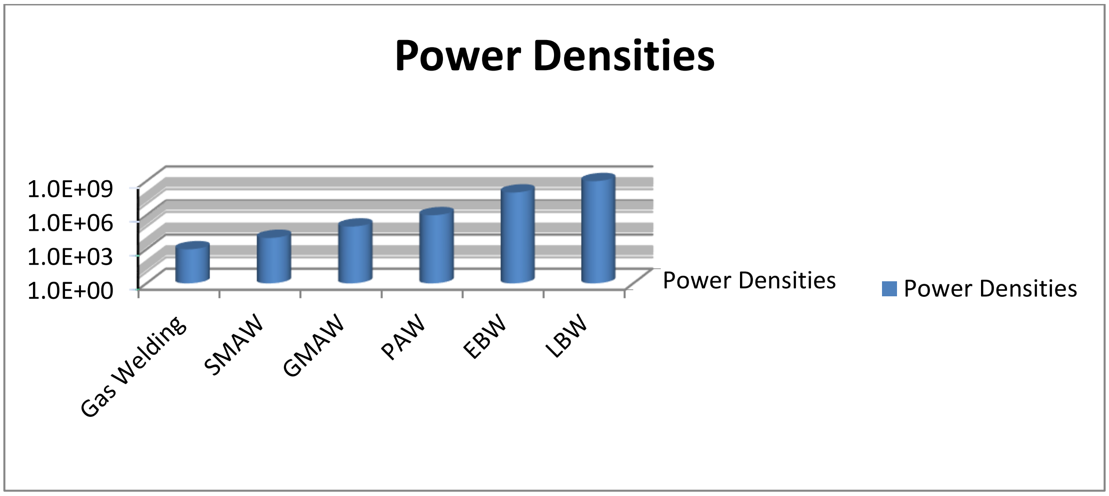


Figure 5: Power density Versus various welding process comparison

2.2 HEAT FLOW MECHANISM IN FUSION WELDING

The heat flow plays a vital role in producing quality sound weld because heat flow in parent metal has a direct effect on following essential parameters;

1. Changes in the physical state of the workpiece
2. Transformation of the metallurgical phase
3. Transient thermal stress or residual stress
4. Distortion or metal movement

Therefore, heat source and heat flow directly influence on the condition of the welded joint after welding and if discontinuity produced then this discontinuity will be only either due to sudden excessive cooling or brittle microstructure or thermal/residual stress or presence of incompatible plastic strains. A heat source moves as welding progress along the length of the joint and leaves the welded joint in the transient thermal state once the heat source is either terminated. Since heat source is in continuous movement, therefore, heat source centre incompletely coincides with moving coordinate throughout the length of the welding joint. This movement of a heat source with moving coordinate produces HAZ, WM and BM zone. The highest temperature achieved, and rate of cooling define heat affected zone metallurgical structure and solidification structural of the weld pool is determined by the thermal gradient which controls the solidification and cooling rate at the liquid-solid junction. Whereas the flow direction and amount of weld pool determine the penetration depth of the welding joint as referring in Figure 6 (courtesy of welding metallurgy by Sindo [2];

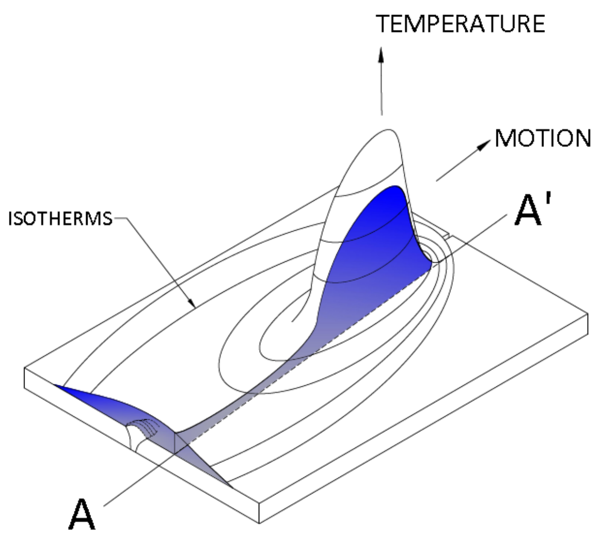


Figure 6: Temperature gradient along with the length of the weld joint

2.3 REACTION IN WELDING

There is a different type of reactions present in welding which upset mechanical and chemical properties of the weld and determine the quality and soundness of completed welded joint. Following are the reaction or interactions discussed in this chapter [2];

1. Gas-metal reactions

2. Slag-metal reaction

2.4 GAS METAL REACTION

The reaction of gas such as oxygen, nitrogen, and hydrogen with molten metal is known as a gas-metal reaction. In this reaction gases such as oxygen, nitrogen and hydrogen come either from outside air, from grease, from moisture, from electrode coating and decompose due to high arc temperature into atomic gas and dissolve into molten metal from the centre because of high heat or temperature. Below in Table 1 is a summary which explains the effect of gas-metals reactions; Table 1 is generated on the discussion from the book "welding metallurgy" by Sindo [2];

Table 1: Different metals effects on weld pool

	Nitrogen	**Oxygen**	**Hydrogen**
Steels	Increase Strength but reduces Toughness	Reduces toughness but improves it if acicular ferrite	Induce hydrogen cracking
Austenitic or Duplex Stainless Steel	Reduces Ferrite and Promotes Solidification cracking	-	-
Aluminium	-	Forms Oxide Films that can trap as inclusion	Form Gas porosity and reduces both strength and ductility
Titanium	Increase strength but reduces ductility	Increase strength but reduce ductility	-

Nitrogen, the molten metal reaction is only significant in case of metals such as Fe, Ti, Mn and Cr that react with nitrogen and produce nitrides. Since nitrogen is an austenitic stabiliser, therefore, increasing nitrogen reduce ferrite content in duplex stainless steel due to which risk of facing solidification cracking increased. Nitrides have a needle-like structure, and the sharp end of these nitrides are initiation points for cracking. Due to this fact, ductility and impact toughness reduces by increases of nitrogen to molten metals reaction. To avoid the nitrogen-molten metal reaction, strong nitrides former such as Ti, Al, Si and Zr added which react with atomic nitrogen and nitride enter into slag.

In the same way, the oxygen-molten metal reaction also works and reduce ductility and toughness by an increase of oxygen to molten metal reaction however at nucleation site if acicular ferrite produced then there is little improvement of toughness observed.

Hydrogen amount in the weld metal is another crucial factor for producing sound welds. Presence of atomic hydrogen in weld metal leads to hydrogen induced cracking, porosity and lowering f ductility and strength only for aluminium alloy. Therefore, the amount of dissolvable hydrogen controlled which is done by the gas chromatography method and mercury method. In the mercury method, a small test coupon is welded and immersed into mercury whereas mercury placed into eudiometer tube. With time hydrogen starts diffuses out of test immersed specification which leads drop in hydrogen level in eudiometer and in this way, we measure the amount of diffusible hydrogen by comparing the final level of hydrogen in eudiometer tube, after many days of the test at room temperature. Therefore, the mercury test method is prolonged especially as compared to gas chromatography method where test coupon is placed in a leak-tight chamber where its coupon is heated to increase the hydrogen evolution time, once hydrogen is evolved then the leak-tight chamber is connected to gas chromatography analyser to measure the amount of hydrogen produced.

Following method is established to avoid the effect of hydrogen;

1. Shield gas with either no hydrogen or low amount of hydrogen
2. Use a dry electrode to avoid moisture
3. Adjust the composition of consumables

2.5 SLAG-MOLTEN METAL REACTION

Slag to metal reaction occurs at the interface of molten slag and molten parent metal. Slag-metal reaction affects the soundness of completed weld because this reaction is affected due to the decomposition of oxides and oxidation of elements due to dissolved oxygen. Decomposition of oxide done due to a high-temperature zone near welding plasma. The oxide classified as a basic oxide which are donors of atomic oxygen, an acidic oxide which is acceptors to atomic oxygen and a neutral oxide such as amphoteric oxides. Type of oxide hurts weld quality, therefore, the basicity index calculated as per the below-given Equation 3 (courtesy of welding metallurgy by Sindo [2]) ;

$$BI= \sum (\text{\% basic oxides}) \div \sum (\text{\% non-basic oxides}) \tag{3}$$

2.6 FLUID FLOW OF MOLTEN METAL IN WELDING

There is following a different type of fluid flow in welding which summarised into tabulated form. The fluid flow must be carefully understood because it influences deposition, penetration depth and heat affected zone, therefore it also indirectly affects the soundness and mechanical properties of completed welded joints.

Following are the forces and fluid flow present during the welding process;

1. Fluid flow and acting forces in the weld pool zone
2. Fluid flow and acting forces in an arc from electrode tip to the molten surface

Refer below for driving force on a different region of fluid flow; Table 2 is a summary of the discussion from book welding metallurgy by Sindo [2];

Table 2: Driving force on a different region of fluid flow

Sr.	The region of Fluid Flow	Driving Force	Formula	Remarks	Mechanism
01	Weld Pools	Buoyancy Force	$BF=\rho\times V\times g$	BF=Buoyancy force ρ = Density g = Gravity	
		Lorentz Force (Electromagnetic Force)	$\vec{F}=q\vec{v}\times\vec{B}$	$\vec{F}$ = force q = Charge $\vec{v}$ = Velocity $\vec{B}$ = Magnetic field	
		Shear Stress due to surface tension gradient (at the molten metal surface)	$Ma=-\frac{d\Upsilon}{dT}\frac{L\Delta T}{\alpha\mu}$	Ma = Marangoni number Υ = Surface Tension L= Characteristic Length α = thermal Diffusivity μ = Dynamic Viscosity ΔT = Temperature Gradient	Marangoni Effect due to surface tension in the absence of Surface-Active agent
		Shear Stress-induced due to Arc plasma on the molten metal surface	$Ma=-\frac{d\Upsilon}{dT}\frac{L\Delta T}{\alpha\mu}$	Ma = Marangoni number Υ=Surface Tension L= Characteristic Length α = thermal Diffusivity μ = Dynamic Viscosity ΔT=Temperature Gradient	Marangoni Effect due to surface tension in Presence of Surface-Active agent
02	Fluid Flow in Arc (The forces which effect Droplets movement)	Gravitation Force (Due to the mass of droplet)	$F_g=\frac{4}{3}\pi R^3\rho_d\,g$	F_g = Gravitation force R = Droplet Radius ρ_d =Droplet Density	
		Drag Force (Due to flowing shielding gases)	$F_d=C_d\frac{\rho v^2}{2}\pi R^2$	F_d=Drag Force C_d=Drag Coefficient V = Flow Velocity	
		Electromagnetic Pinch Force	$F_{em}=\frac{\mu_0 I^2}{4\pi}\ln\frac{r_a}{R}$	r_a=Radius of Arc μ_0=Permeability of free space	

		(Due to Arc Pressure or detaching Forces or Lorenz Force)			

2.7 CARBON EQUIVALENT

Carbon plays an essential role in producing a quality weld. Carbon equivalent derived whose intent is to consider the effect of all alloying element of parent metals and reflects their effects in terms of carbon and carbon equivalent is the sum of carbon content plus the effects of all other alloying elements. The purpose of all these efforts is to estimate the weldability, find preheating / post heat treatment requirements and the probability of getting welds, hardness and hardenability of the completed weld are directly, and weldability of the parent metal is inversely optional to carbon equivalent number. American welding institute and derived Equation 4 which is used to estimate hardness, hardenability, and weldability of the parent metals [1];

$$CE=\%C+\left(\frac{\%Mn+\%Si}{6}\right)+\left(\frac{\%Cr+\%Mo+\%V}{5}\right)+\left(\frac{\%Cu+\%Ni}{15}\right) \quad (4)$$

If carbon equivalent (CE) is less than 0.35, then weldability is excellent and is poor if CE is over 0.50. We have used ASTM A572 material for FCAW, and ASTM A36 for GMAW process and both materials have CE < 0.30 % [1].

Japanese welding engineering society used a critical metal parameter as shown in Equation 5 instead of carbon equivalent, and the critical metal parameter is used to find susceptibility of parent metal weld cracking.

$$\text{Pcm}=\%\text{C}+\frac{\%\text{Si}}{30}+\frac{\%\text{Mn}+\%\text{Cu}+\%\text{Cr}}{20}+\frac{\%\text{Ni}}{60}+\frac{\%\text{Mo}}{15}+\frac{\%\text{V}}{10}+5\% \qquad (5)$$

In carbon equivalent and critical metal parameter, only those elements other than carbon considered that have a direct influence on hardness, hardenability, weldability, toughness, and strength [1].

2.8 FERRITE NUMBER

Ferrite number is the parameter which shows the total amount of delta ferrite in the completed weld of austenitic steel. Ferrite number acceptable range is 5-20. Ferrite number plays an essential role in the quality of completed weld for austenitic steel. If ferrite number is lower than five then completed weld might undergo hot cracking; however austenitic steel weldment's protection against corrosion increased at the lower ferritic number. Higher ferrite number might lead to brittle failure of weldments if welded austenitic joints exposed to higher temperature [3];

$$\text{Fn} \quad \alpha \quad \frac{1}{\text{Cooling Rate}} \qquad (6)$$

The acceptable range of ferrite number can be decided base on service requirements such as high toughness for cryogenic services, resistance to a corrosive environment and magnetic permeability. However, the ferrite number is inversely proportional to the cooling rate of weldments during or after welding and can be controlled by electrode size/diameter, current and heat input. Ferrite number relation with cooling rate mentioned in Equation 6 (courtesy of ASM welding handbook vol 6 [1]). Ferrite number measured by ferrite meter or Severn gage or mahne gage where these instruments work on the principle that ferrite is a magnetic material and austenitic is nonmagnetic material. If ferrite content is more than the measured intensity of the magnetic field will be more.

2.9 PREN NUMBER

PREN number is defined to assess the corrosion resistance ability of stainless steel. Higher PREN number corresponds to the higher corrosion resistance of steel and PREN is known as pitting resistance equivalent number. Below PREN defined by ASM is given in Equation 7 [1];

$$\text{PREN}=\%\text{CR}+3.3(\%\text{Mo})+16(\%\text{N}) \tag{7}$$

In the above formula, only those alloying elements considered which affects the pitting corrosion resistance.

2.10 PENETRATION INDEX

Penetration index is 100% and 100% value as required by the designer. It defined as the ratio of the depth of weld deposited to the thickness of parent metal. Based on the discussion in ASM welding handbook vol 6 [1], Equation 8 derived for clear understanding;

$$\text{Penetration Index }(\%)=\left(\frac{\text{Depth of weld Bead}}{\text{Parent Metal thickness}}\right)\times 100 \tag{8}$$

With the reference of the above expression, for incomplete penetration, the index will be less than 100 and excess penetration, the index will be higher than 100.

2.11 CONVEXITY INDEX

Convexity defined as the ratio of bead reinforcement to the bead width, and expressed in Equation 9 based on the discussion in ASM welding handbook vol 6 [1];

$$\text{Convexity Index (\%)}=\left(\frac{\text{Bead Re-inforcement}}{\text{Bead Width}}\right)\times 100 \tag{9}$$

2.12 SPATTERING INDEX

Spattering rate defined as the ratio of spattering rate of melted metal to the deposition rate of the electrode and it is expressed in Equation 10, 11, 12, 13 and 14 based on the discussion in ASM welding handbook vol 6 [1];

$$\text{Spattering Index (\%)}=\left(\frac{\text{Spattering Rate}}{\text{Deposition Rate of Filler metal}}\right)\times 100\ . \tag{10}$$

$$\text{Spattering Rate }\left(\frac{\text{kg}}{\text{h}}\right)=\text{Fusion rate of wire or electrode-Deposition Rate} \tag{11}$$

$$\text{Fusion rate of Wire}= 60\times\left(\frac{\pi\times\emptyset 2\times\gamma\times\text{wire feed rate}}{4}\right) \tag{12}$$

$$\text{Deposition Efficiency(\%)}=\frac{\text{weight of weld metal}}{\text{weight of electrode used}} \tag{13}$$

$$\text{Deposition Efficiency (\%)}=\frac{\text{Deposition rate }\left(\frac{\text{kg}}{\text{hr}}\right)}{\text{Burn off rate }\left(\frac{\text{kg}}{\text{hr}}\right)} \tag{14}$$

2.13 HEAT INPUT

Heat input measures the amount of energy or heat supplied to parent metal to produce welded joints. The heat input relation with travel speed, arc voltage and arc current provided in Equation 15 (courtesy of ASM welding handbook vol 6) [1].

$$\text{Heat Input}\left(\frac{\text{min}}{\text{mm}}\right)=\text{arc current}\times\text{arc voltage}\times\frac{0.06}{\text{travel speed}} \qquad (15)$$

2.14 PROCESS PARAMETERS FOR FCAW/GMAW

Following are the basic parameters which affect the qualification of any arc welding process. All international standards consider these parameters while defining their essential/non-essential and supplementary essential variables [4];

1. Type of base/parent metal
2. Type of filler metal
3. Welding positions and weld joint design
4. Preheating and post weld heat treatment
5. Types of gases
6. Techniques
7. Electrical characteristics

2.14.1 BASE METAL

The material subjected to weld before engaging with the welding electrode is called a base metal in welding science. ASME had formulated group welding base metal having similar properties and named each group with p-number. ASME assigned P1 to P15 numbers to ferrous material summary of ASME designation for parent metals is given in Table 3. for the thesis, we have taken ASTM A572 Gr 50 type I and ASTM A36 materials for FCAW and GMAW respectively which belong to P1 group of ASME [4];

Table 3: Parent metals ASME grouping base on material behavioural

P Numbers	Base Metals	Sub-Detail
1 through 15F	Steel and Steel alloys	P 1 - Mild Carbon Steel
		P 3 - Low Alloy Steels
		P 4 - Chrome-moly Steels (1-1/4)
		P 5 - Chrome-moly Steels (2-1/4)
		P 8 - Stainless steel

There are some materials and grades which are introduced by other international standard material organisations like ASTM, API or AISI which are acceptable to ASME but not listed in their classification. So, such materials give S-numbers. However, now P-numbers are re-assigned to those metals which were previously assigned S-numbers. AISI has categories materials as per the following Table 4 [4];

Table 4 : AISI - SAE parent metals grouping system

AISI-SAE Classification (Grade/Material)			
10XX	Plain Carbon steel	43XX	Ni-Cr-Mo Steels
11XX	Re-sulphurated grades	51XX	.8% Cr Steel
13XX	Manganese Steels	52XX	1.45% Cr Steels
40XX	Mo Steels	61XX	Cr-V Steels
41XX	Cr-Mo Steels	92XX	Si-Mn Steels
50B60	Boron Treated Steel		

These classifications divide ferrous and non-ferrous metals into different groups' base on their chemical composition and mechanical properties. The following Table will show a different type of ferrous metals, their major alloying elements and essential properties which make them useful in different areas of industry. Whereas famous non-ferrous metals include copper and copper alloys, Ni and Ni alloys. Aluminium and Aluminum alloys, titanium and titanium alloys. Refer to Table 5 for more detail (courtesy of ASME section ix and ii [4]);

Table 5: Weldable material classification relating to the chemical composition

<table>
<tr><td colspan="3">CARBON STEEL</td></tr>
<tr><td rowspan="3">C less than 1%, Mn less than 1.65% and C, Si less than .60%, weldability depends upon Carbon contents</td><td>Low Carbon Steel</td><td>0.10 to 0.25% C, 0.25 to 1.5% Mn, widely used and easily weldable by any process</td></tr>
<tr><td>Medium Carbon Steel</td><td>0.25 to 0.50% C, 0.60 to 1.65% Mn, readily weldable by any process with proper preheat</td></tr>
<tr><td>High Carbon Steel</td><td>0.50 to 1.03% C, 0.30 to 1% Mn, readily weldable by any the process with proper preheat/PWHT</td></tr>
<tr><td colspan="3">Alloy Steel</td></tr>
<tr><td>Low Alloy Steel</td><td colspan="2">Mn more than 1.65%, Si and Cu more than 0.60% and mini 3.99% of Co, Cb, Mo, Ni, Ti, W, V or Zr, easily weldable if base metal receives proper preheat and proper weldment PWHT</td></tr>
<tr><td>High Alloy Steel</td><td colspan="2">More % age values of alloying elements, Pitting resistance equivalent use which is = %Cr+3.3%Mo+16%N, AWS A4.2 and ASTM E562 are used to find Ferrite contents</td></tr>
<tr><td colspan="3">Stainless Steel</td></tr>
<tr><td rowspan="3">Contains 11-30% Cr, Low melting temperature and thermal conductivity and higher coefficient of thermal expansion with good corrosion resistance</td><td>Austenite</td><td>Mostly used with excellent corrosion resistance, weldability and ductility with good high T oxidation resistance but susceptible to Pitting and Chloride SCC</td></tr>
<tr><td>Martensitic</td><td>C up to 0.35%, Cr 11.5 to 18%, Magnet and High hardness, so welding requires to preheat/PWHT, susceptible to HIC during welding, used for cutlery and surgical instruments</td></tr>
<tr><td>Ferritic</td><td>11.5 to 30% Cr, Magnet and nonhardenable by heat treatment limited weldability due to low</td></tr>
</table>

		HAZ toughness, susceptible to embrittlement, used for heat exchanger tubes
	Duplex	Combine effect of ferrite and Austenite phases, resistance to chloride SCC and SSC, High strength, good toughness, and ductility
	Precipitation Hardened	High strength and Mo, Ti, Cd, Al used as precipitation hardening promotors, Few types are non-weld able, but some are which do not require Preheating

We have used medium carbon steel for the thesis.

2.14.2 WELDING CONSUMABLES

The metal which is used to fill the welding groove is known as a filler wire. However, the selection of filler wire is very critical which based on the base metal strength and chemical composition. ASME had also formulated welding consumables groups, and each group is named as F-Numbers as mentioned in Table. F- numbers of filler metals are considered essential, and any change from one F-number to any other F-number or any metal not listed here will require requalification. The following Table 6 will show ASME Sec IX (welding and Welder Qualification standard) [4], classifications for F-numbers of different materials.

Table 6: Filler wire number and grouping base on material properties

F Numbers	Materials
1 through 6	Steel and Steel Alloys

ASME had also assigned "A" number" to each F-Number providing the detail chemical composition of metal as explained in Table 7; we have used in thesis welding consumables having F-6 and A- 1 E71T-1C from SFA 5.36 for FCAW process and ER 70S-6 from AWS

5.18. Chemical composition grouping number designated by A as shown in Table 7 [4];

Table 7 : Chemical composition grouping number designated by A

A Number	Type of weld Deposit
1	Mild Steel
2	Carbon Moly
3	Chrome (up to 2%)-moly
4	Chrome (2% to 4%)-moly
5	Chrome (4% to 10.5%)-moly
6	Chrome - Martensitic
7	Chrome - Ferritic
8 and 9	Chrome - Nickel
10	Nickle up to 4%
11	Manganese-Moly
12	Nickle- Chrome - Moly

2.14.3 PREHEAT

Preheating is the process of heating the base metal up-to required temperature before the start of welding. Preheating of base metal will reduce the temperature gap between metal temperature before welding and welding temperature, and it is only to avoid microstructural changes in the base material. Preheating shall apply to all side of welding joint including heat affected zone.

Table 8 is the extract gathered from the international standard for the thesis specific material P. For The material used for GMAW and FCAW processes only 50 Fahrenheit preheating was done as it is in line with international standard and approved WPS [5].

Table 8: Preheating welding in different international standards

P-Number	ASME Section-1	ASME Section-8	ASME B31.1	ASMEB31.3
1 (CS)	175^0F for C> 0.3% and t> 1” otherwise 50^0F			50 ^{0}F for t < 1” and T_s = 71ksi 175 ^{0}F for t <1” or T_s> 71ksi

2.14.4 POST WELD-HEAT TREATMENT (PWHT)

Post weld heat treatment is used to reduce residual, interlocking stresses in the material and to improve dimensional stability along with resistance to stress corrosion cracking (SCC). PWHT is also helpful to reduce hardness in the material which may cause SCC embrittlement.

Applicability of PWHT base on the following factors;

1. Based on service fluid chemical composition, for example. Caustic soda, H_2S et cetera.
2. Based on base material thickness
3. Based on the chemical composition of P-number. For example. P4 and five are always subjected to PWHT

PWHT temperature and time range become essential in case of notch toughness requirements. Because these will affect the impact properties of the material. So, any change in these values will require requalification of the procedure as per ASME Sec IX for any welding process. Thesis specific PWHT requirements extracted in Table 9 from ASME international standard. Table 9 shows that PWHT does not apply to the material used for the Thesis [5].

Table 9: PWHT requirements after welding in different international standards

P-Number	ASME Section-1	ASME B31.1	ASME B31.3	ASME Section-8
1	1100 ^{0}F for t>3/4”			1100 ^{0}F for t>1.5” Or 1.25” $<t<$ 1.5” and $T_p < 200$ ^{0}F

2.14.5 TECHNIQUE AND WELDING PROGRESSION

Techniques include processes such as progression direction, deposition of weldment in a single pass or multipass and back gouging of the root pass. Changes in qualified techniques are essential variables because changes will affect the notch toughness of the material [4].

2.14.6 PURGING GASSES

GMAW and dual shielded FCAW welding processes use a different type of shielded gasses. Typically helium, argon, CO_2 or their blend along with some addition of H_2 and O_2 are used. Type of gases affects the weldment and properties, so few characteristics of gases classified as essential variables in some standards. Moreover, they ask for requalification in case of any change from one single shielding gas to another or a mixture of shielding gasses. Sometimes deletion of shielding gas or change in the nominal composition will also require requalification especially for root pass and may cause root defects during root and hot pass run of welding [4];

2.14.7 ELECTRICAL CHARACTERISTICS

Any increase in heat input and deposited weld metal volume over the qualified range will consider when there are impact test requirements. In both cases, there will be a change in heat values absorbed by the material so that impact strength values can be changed. Heat input can calculate from Equation 16 (Courtesy of ASM welding handbook vol 6 [1]);

$$\text{Heat Input}\ \left(\frac{\text{j}}{\text{mm}}\right)=\frac{(\text{Voltage})(\text{Amperage})(60)}{\text{Travel Speed}\ \left(\frac{\text{mm}}{\text{min}}\right)} \tag{16}$$

Moreover, the volume of weld metal can be measured by an increase in bead size. In notch toughness requirement current polarity is also an essential variable so any change from AC to DC or straight polarity to reverse polarity will also require considering because this will affect the heat input values.

2.14.8 WELDING POSITION AND WELD JOINT DESIGN

Welding position is vital because few processor modes of operation are dependable or give a better quality of weld on specific welding position. For example, the SAW performed in a flat position, short circuit mode of GMAW in an overhead position and spray mode of GMAW in horizontal and vertical positions.

Weld joints design is also fundamental in terms of distortion. Both butt and fillet joints may experience distortion. However, distortion can minimise by changing the type of joints like butt versus fillet single versus double side joint. Weld volume in joint affects local expansion and contraction. So, more volume means more value of distortion. Therefore, in this way weld joint design play a role. Typically, five different types of joints are used which are butt, corner, edge, lap and tee joints. For the thesis, we used horizontal welding position and groove bevel as joint design [4].

2.15 WELDING PROCEDURE SPECIFICATION (WPS)

The welding procedure is a document which gives direction to welder or operator for making any weld. in other words, the purpose of qualifying welding procedure is to verify that the test weldment's mechanical and metallurgical properties are acceptable for the intended service of the weldment. WPS is the responsibility of any manufacturer or contractor who is going to start welding so that specific WPS becomes his property. WPS made according to the international construction standards applicable to that scope of work. For healthy plant/onshore/tanks/pressure vessels ASME sec ix is followed for the qualification of WPS, for cross country pipelines API 1104 whereas, for carbon steel structure welding, AWS D1.1 used for qualification. WPS specify the conditions or ranges which shall follow for welding. Therefore, variables divided into different categories depending upon their effect on the strength of welding joint and WPS enlisted those variables along with their ranges. Each WPS at least contain essential and non-essential variables and sometimes supplementary essential variables if applicable. So naturally, we can say WPS determines that any specific weldment proposed for the job can provide the required properties. WPS can be revised in case of any change in nonessential variables or due to any further supporting pqr but remember any change in an essential variable of that WPS will require requalification of WPS. Welding procedure used for GMAW/FCAW processes attached in the Appendix-I [4].

2.16 PROCEDURE QUALIFICATION RECORD

Procedure qualification record commonly named as PQR is a document which occurred during welding of test coupon and testing results of that coupon. It should include at least all essential variables of that process which proposed for that test coupon along with other required variables. Sometime PQR contains supplementary essential variables when impact test or notch toughness testing required for that job. As a successful acceptance of test results PQR is used to develop WPS but within the applicable ranges allowed by international code. PQR cannot be revised, but any change in essential variables will require requalification of PQR. Sometimes two or more PQRS can be used to develop one WPS, or two or more WPSs can also be made from one PQR but within the ranges for which it initially qualified. Test results will remain part of PQR for future references.

The following steps took for performing PQR and then after to develop WPS accordingly;

1. Drafting the preliminary WPS (PWPS) to perform test coupon welding and here preliminary variables (unapproved WPS) are selected according to parent material for which test coupon is going to weld as per applicable qualification standard and previous experience.
2. Weld test coupon designed according to desired thickness and diameter, and all actual parameters noted during the welding
3. Welding the test coupon as per PWPS at that welding position which will qualify the desire welding position
4. After completion of welding testing of the coupon is performed to find soundness of the weldment
5. The results evaluated according to the acceptance criteria given in standards

6. Documenting the test results
7. WPS is developed with compliance of PQR as per qualification code such as ASME Sec IX, API 1104 AWS D1.1 et cetera.

As mention above PQR contains all essential variables and WPS include essential and nonessential variables. Now we shall discuss parameters which are considered during qualification and classified as essential, nonessential and supplementary essential variables [4].

2.16.1 ESSENTIAL VARIABLES (EV)

A welding condition that will affect the mechanical properties of a weldment if that condition is changed. So, it is essential to note that any change in an essential variable will require requalification of WPS [4].

2.16.2 SUPPLEMENTARY ESSENTIAL VARIABLES (SEV)

A welding condition that will affect the impact strength of weldment due to heat input changes if the condition is changed. Impact strength is the material's ability to absorb load energy rapidly applied to the part. Impact testing is carried out at a specified temperature whereas code or type of base metal dictates the minimum and average values of absorbed energy [4].

2.16.3 NON-ESSENTIAL VARIABLES (NEV)

A welding condition that does not affect the mechanical properties of a weldment if the condition is changed. All type of non-essential variables defines by any standard do not require requalification if need to be changed. However, one thing is vital that once non-essential variables written on WPS need to change then, WPS will be revised to depict those changes instead of doing the new changes on the same revision of existing WPS.

ASME Sec IX defined essential, non-essential and supplement variables for all welding process. Since the thesis is spherically for GMAW and FCAW welding processes, therefore we have extracted the information from ASME Section IX for GMAW, and FCAW processes and formulated the Table 10 [4].

Table 10: Essential, non-essential variable for the welding process

Variables	Brief of Variables	EV	SEV	NEV
Weld Joint	Groove Design			X
	Backing			X
	Root Spacing			X
Base Material	Group Number		X	
	T limits		X	
	T Qualified	X		
	P Number	X		
	t Pass	X		
Filler Metal	F Number	X		
	A Number	X		
	Diameter			X
	Alloy Flux	X		
	Flux product form	X		
	Thickness t	X		
	Classification		X	X
Welding Position	Position		X	X
Preheat	Decrease more than 100F	X		
	Increase more than 100F		X	
PWHT	PWHT	X		
	PWHT Temp. moreover, Time range		X	
	T limits	X		
Electrical Characteristics	Heat Input		X	
	Transfer Mode	X		
	Current/polarity		X	
Gas	Trail or composition			X
	Single/Mixture or %age	X		

	Flow Rate			X
	Backing flow			X
	Backing or Composition	X		
	Shielding/Trailing	X		
Technique	String/Weave			X
	method of Cleaning			X
	method back gouge			X
	Oscillation			X
	Multi/Single Pass vice versa		X	
	Manual/Automatic			X
	Peening			X
	Thermal Processes	X		

CHAPTER 3

QUALITY CONCERNS AND LITERATURE REVIEW

Before start of the design of experiments, major quality concerns are documented in chapter three which will help in selecting the appropriate welding's factors and responses. The latest literature study is also conducted to consult the on-going trend for the optimization of GMAW/FCAW.

3.0 QUALITY ISSUES OF WELDING

Welding defect and discontinuities are quality issues in welding . International standards had documented the acceptable tolerances of welding defects and discontinuities; however, the author has listed down some major quality issues which are frequently observed in the outdoor welding.

3.1 LACK SIDE WALL FUSION

This type of defect is typically found in GMAW while welding thick section in the vertical down position. Lack of Side Wall mainly caused by the inherent coldness of this form of metal transfer, and the action of gravity, but may also attribute to incorrect settings and possible lack of welder skill. Defect's orientation and the location is shown in Figure 7 (courtesy of TWI global [6]);

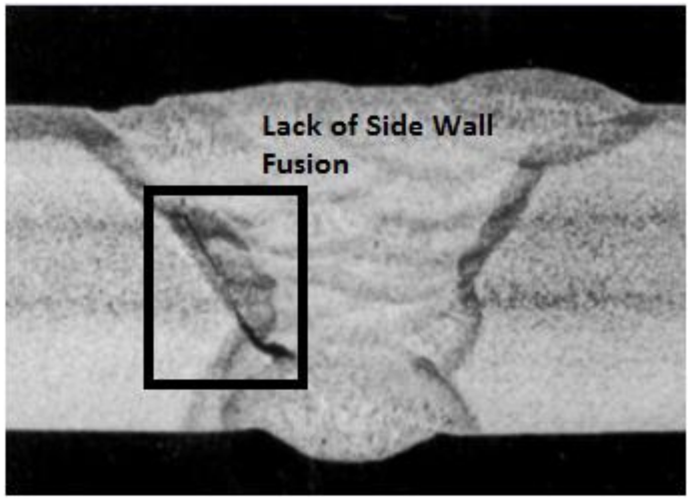


Figure 7: Lack of sidewall fusion

3.2 POROSITY

Porosity caused by loss of gas shield and low tolerance to contaminants. A singular gas porosity cavity filled more than 1.5mm diameter is termed as blowhole porosity and can occur during GMAW due to shielding gas loss and the entrance of air into a column of the arc and sometimes due to the false setting of shielding gas flow rate. Defect's orientation and the location is shown in Figure 8 (courtesy of TWI global [6]);

Figure 8: Porosity weld defect

3.3 BURN THROUGH

There will burn through when incorrect metal transfer mode on sheet metals used. Excessive penetration bead follows by the collapse of the weld root in the affected area may cause burn through. It may generally cause by other factors like welding current, root gap, root face and travel speed. Defect’s orientation and the location shows in Figure 9 (courtesy of TWI global) [6] ;

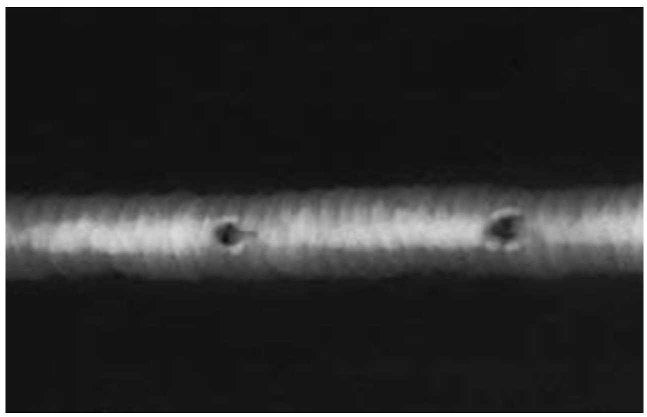


Figure 9: Burn through

3.4 SILICA INCLUSIONS

Find in ferritic steel only due to poor inter-run cleaning. Because in MIG/MAG use Si, Al, and other elements to deoxidise the weld. These may form silica or aluminium inclusions. Any of these non-metallic compounds may trap inside the weld. An incorrect welding technique mostly causes these. Defect’s orientation and the location shows in Figure 10 (courtesy of TWI global) [6];

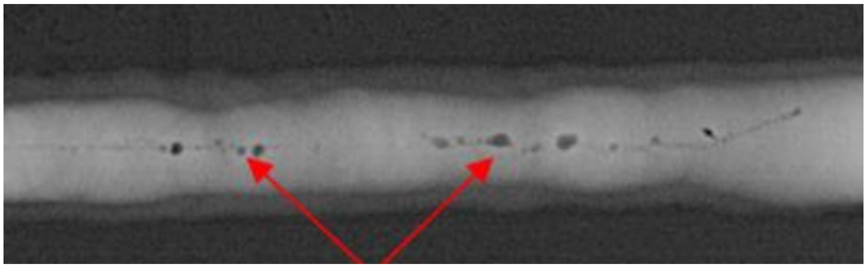


Figure 10: Silica inclusions

3.5 STANDARD AND FIELD PRACTICE TO MINIMIZE THE QUALITY ISSUES

To minimise the quality issues following field and standard practised are employed;

1. Specify the essential variables of the welding process
2. Essential variables considered as significant factors
3. International Standard such as ASME, AWS et cetera is followed to select the Upper and lower controllable limits of significant factors.
4. Test piece welding execution performed as procedural qualification terms as WPS Qualification
5. All personnel assigned to perform the welding tested before performing the welding known as welders' performance qualification.

Below are tolerances permitted by International Standard ASME B31.3 in Table 341.3.2 and extract is given below in Table 11 [5];

Table 11: Defects tolerances permitted by ASME B31.3 for pressure welds

Sr.	Defects Type	Permitted Tolerance
1	Rounded indication	For $T_w \leq 6$ mm (1⁄4 in.), the limit is the same as D For $T_w > 6$ mm (1⁄4 in.), the limit is 1.5 _ D

2	Elongated indication	Individual length ≤2*T w* Individual width ≤3 mm (1⁄8 in.) and ≤*T w* /2 Cumulative length of ≤4Tw. in any 150 mm (6 in.) weld length
3	Burn Through	Total joint thickness
4	Root concavity	Total joint thickness
5	Capping convexity	Total joint thickness
6	Weld Reinforcement	1.5mm for Two < 6mm 3mm for Tw >6mm<13mm 4mm for Tw >13mm<25mm 5mm for Tw >25mm
7	LOP	Zero
8	LOF	Zero

3.6 NEED FOR OPTIMIZATION IN-SPITE OF CODE/STANDARDS

The code/standard are collaborative experiences from welders and consumers voice which have recommended broad process parameters tolerance for the acceptable product (weld) quality, but within that recommended window still, there is a scope to find the further narrowed down optimum or near optimal process parameters settings. Therefore, in search of such conditions, desirability analyses are selected to perform optimisation for FCAW/GMAW processes.

3.7 LITERATURE REVIEW FROM PAST PUBLICATIONS ON WELDING PROCESS (GMAW/FCAW) OPTIMIZATION

Many Types of research investigated and suggested a methodology to elaborate the welding process parameter effects on weld joint mechanical strength, weld quality, weld appearance et cetera we will discuss the literature review for GMAW and FCAW optimisation in detail to find the trend in publications;

Yalamanchili, el at. [7] Studied Robust virtual welding process optimisation. He tried to find out the weld sequence optimisation for thick section welding. He used VFT (caterpillar's Proprietary software) for simulation via finite element analysis and then the results were modelled on combinational genetic algorithm and robustness was evaluated based on uncertainty quantification (UQ). He found the optimised weld sequence for the caterpillar. Bitharasa, el at. 2018 [8] Studied visualisation and optimisation of shielding gas coverage during GMAW. He used Schlieren Imagining finding the density gradients and flow characteristics, and 2D and 3D model of FEM validated by schlieren imaging. He found that time and composition of shielding gas which gives the best weld quality. Sarin, el at. 2018 [9] studied the optimisation of GMAW on difference iron-based material by Taguchi methodology, He used ANOVA to predict important welding parameters, and he found that 41.95% of material contributing parameters which affects heat affected zone properties. Ghosh, el at. 2018 [10] studied parametric optimisation of the GMAW process by PCA based Taguchi method on Austenitic Stainless Steel AISI 316L and found that optimal setting of welding parameter for a specific condition. Choudhury and Chandrasekaran et al. 2017 [11] investigated the weldability of nickel base allow by Gas metal process and found it is suitable with controlled welding essential parameters. Hussain Zuhailawati, M Afiq, Anasyida and Suhaina, el at. 2017 [12] studied the welding investigation and prediction of the tensile strength of 304 SS sheet metal joint by RSM, and he found that smaller size of filler wire has a positive effect on the tensile strength of weldment. Muzaka, el at. 2017 [13] studied on the prediction of welding quality using mahala-Nobis distance method by optimisation welding current for a vertical position welding and found an optimised algorithm model on the excellent quality weld. Prakash et al. 2016 [14] studied the low carbon steel optimisation through an orthogonal array of L9 for material A29 and found the optimal welding parameter through ANOVA. Ghosh, el at. 2016 [15] prepared butt joint of 3mm plate and found current 10A, gas flow rate 201/min and nozzle distance 15mm as optimal parameter based on Taguchi design of an experiment to reduce the risk of getting lack of penetration and number of spatters in completed weld joints. Azadi et al. 2016 [16] studied the optimisation of GMAW over API-X42 material through L36 Taguchi matrix and proposed back propagation neural network (BPNN). Srivastava and Garg et al. 2016 [17] used the response surface method to attain the higher mechanical strength range of mild steel by controlling the process parameters .P Venkadeswaran, R Sakthivel, Kamaraj Chandrasekaran el at. 2015 [18] did optimisation on GMAW welded AA2014 material on welding parameter and found the optimised condition for the quality weld. Shinghmar et al. 2015 [19] also used an orthogonal array to find that arc current have an influence on tensile strength by 41 %, on arc voltage by 20% and gas flow rate by 16 %. Kalita, el at. 2015 [20] studied the current, voltage and shielding gas on the mechanical strength of C20 steel by using an orthogonal array of L9 and ER70S-4 welded the sample and he concluded that welding voltage has a significant effect on mean and variation of the tensile strength of weldment is having 87% and 85% respectively. He found current 200 amp, welding voltage 30V and 8litre/min as the optimal setting of welding. Bharath, el at. 2014 [21] studied the optimisation of 316 stainless steel weld joint characteristics using Taguchi technique and found that welding speed is the most influencing parameter on tensile strength. Meshram et al. 2013 [22] utilised the Taguchi technique with grey relation analysis on Stainless steel 410 to find the voltage and wire feed rate effects on penetration, and reinforcement weld bead and optimal parameter obtained through ANOVA. Patil et al. 2013 [23] studied the welding parameter, and optimisation model prepared between welding input such as current, welding speed, voltage et cetera with a tensile strength of weldments and he found that tensile strength depends on welding speed. Kumar et al. 2013 [24] studied the dissimilar welding joints welded by GMAW and optimised the result by Taguchi orthogonal L9 array and analysis was concluded based on the signal to noise ratios. Patel and Chaudhary et al. 2013 [25] worked with full factorial design experiment to optimise the GMAW responses on AISI 1020 material. Anoop, el at. 2013 [26] studied the effect of weld parameters on microhardness value on aluminium alloy 7039. Ob Signal-to-noise analysis, he found that peak current of 150a and base current at 75 a with pulse frequency of 150 hertz produce weld joint with the highest microhardness. Bataineh et al. 2012 [27] studied the GMAW process to find the effects of welding factors over welding strength; the optimization is done through factorial design methodology and ANOVA. Izzatul et al. 2012 [28] optimised the welding responses such as penetration, microstructural and hardness by utilising robotic GMAW process. Gulhane et al. 2012 [29] produce research by analysis the major influence using Taguchi design of experiment philosophy that showed the effect on all factors. ANOVA was used to determine the influence input factors for a series of a run for FCAW process. Sterjoversuski et al. 2007 [30] studied with Artificial Neural Network (ANN) on the diffusible H2 amount and Cracking process in welds welded by flux-core wire. Kannan et al. 2006 [31] showed the study to investigate the properties of flux-core wire welding's controllable factors on clad (CS to SDSS) parameters. Ferraresi, el at.2004 [32] Studied GMAW welding Optimization using Genetic Algorithms and found that the optimal setting for the highest depth of penetration but he suggested that GA is good optimisation techniques and requires larger population sizes, number of generations.

CHAPTER 4

CUBE COMPOSITE DESIGN (DOE) OF FLUX CORED ARC WELDING (FCAW) BY USING RESPONSE SURFACE METHODOLOGY

Chapter four outlined the complete design of experiments for FCAW and in the end, the developed model is obtained which is further used for the optimisation

4.1 INTRODUCTION TO DESIGN OF EXPERIMENTS

The conventional optimisation process includes many experiment trials whereas the design of experiment (DOE) is an economical way to conduct the experiments for the same purpose. Therefore, the author has utilised the DOE technique for the thesis and step involved mentioned below in Figure 11 based on the theory from introduction to process control by John.

4.2 DOE FOR FCAW PROCESS

Figure 11 present, optimisation steps of FCAW. Figure 12 are photos taken for the FCAW setup used during the study [33].

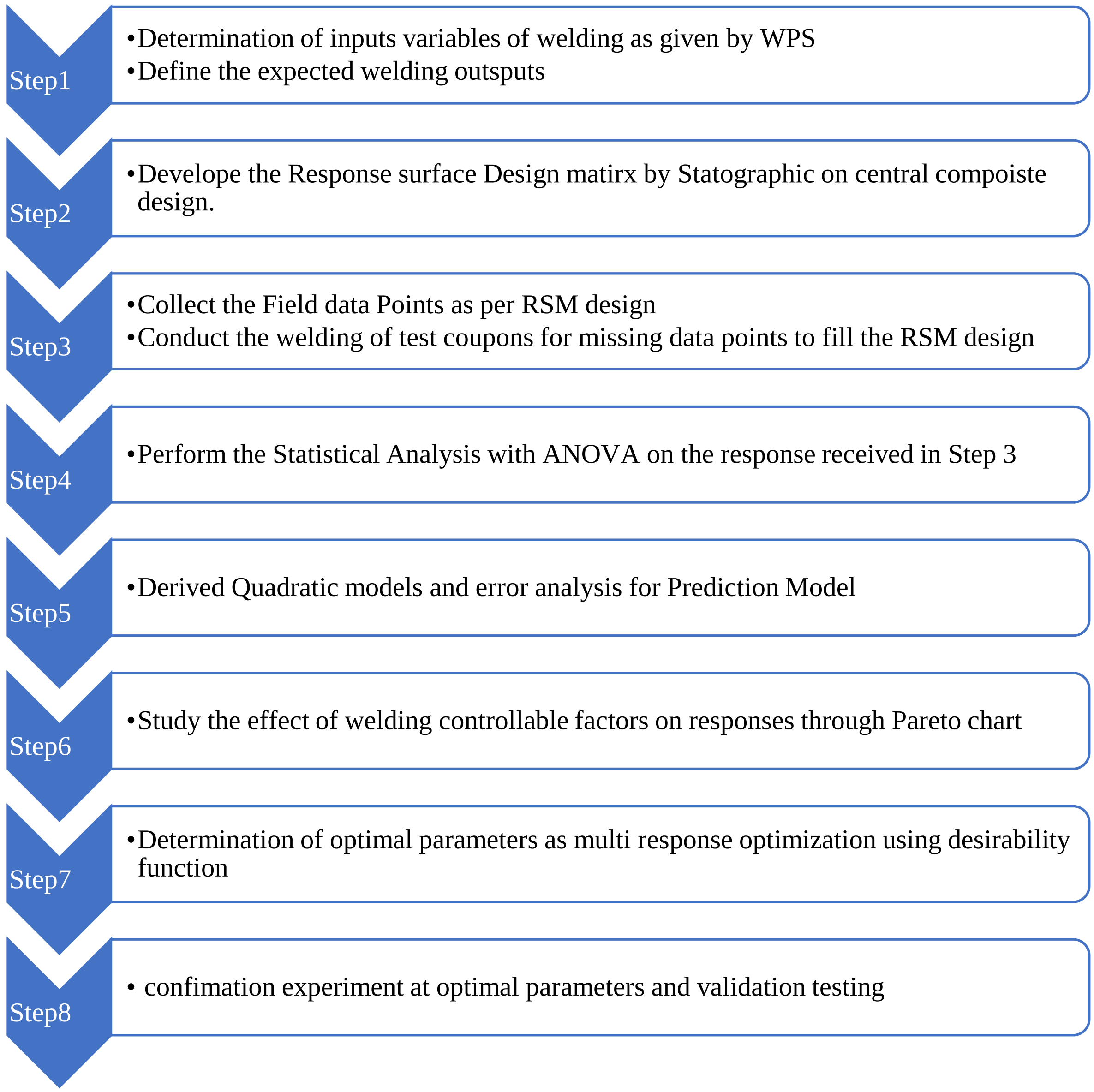


Figure 11: Flow chart for response surface DOE

Figure 12: FCAW welding setup used

The welding was conducted on 25mm carbon steel "ASME A572 grade 50 type 1". Chemical and mechanical composition of parent material are provided below in Table 12 courtesy of manufacturer "Metihbect" country of origin Ukraine.

Table 12: Chemical and Mechanical Properties of material used for FCAW

	Chemical Composition of ASTM A 572 Gr. 50 Type-I (Heat Number 28218)														**Strength (MPa)**	
Sr	C	Mn	Si	S	P	Cr	Ni	Cu	Ti	Al	N	Mo	V	Nb	Tensile	Yield
01	0.15	1.17	0.18	0.017	0.019	0.02	0.01	0.02	0.003	0.03	0.005	0.002	0.003	0.018	500	395

Bevel angle checked with dye penetrant testing for any possible defects like crack et cetera FCAW machine of model Lincoln "idealarc cv400" used for welding whereas reinforcement measured by using Cambridge welding gauge.

The joint welding design is given below in Figure 13;

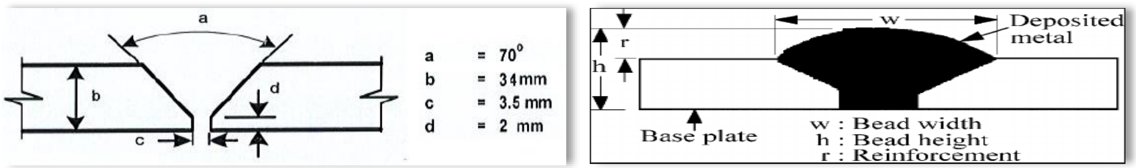


Figure 13: Joint design detail used for FCAW welding (WPS sheet Appendix 1)

Design of experiment is the scientific and engineering way to collect the data matrix. The data matrix will be used to analysis further to find the optimal condition. Figure 14 is a summary of the design of the experiment. Although many researchers have used the different methodology, however, the most composite type of design of the experiment is response surface methodology which is subdivided into the composite design and box Behnken design.

The quantitative relation between responses and factors in term of RSM can express as per Equation 17 [33];

$$\text{Responses } (Y) = f\{\text{Response } X_1 \text{ , Response } X_2 \ldots \text{Response } X_n\} \qquad (17)$$

Whereas Y is the responses and X_1, X_2.... X_n is controllable factors. The system behaviour will be obtained through a quadric model or by higher order polynomial model which is developed by the least square method by considering the interaction of factors to maximise or minimise the response variables,

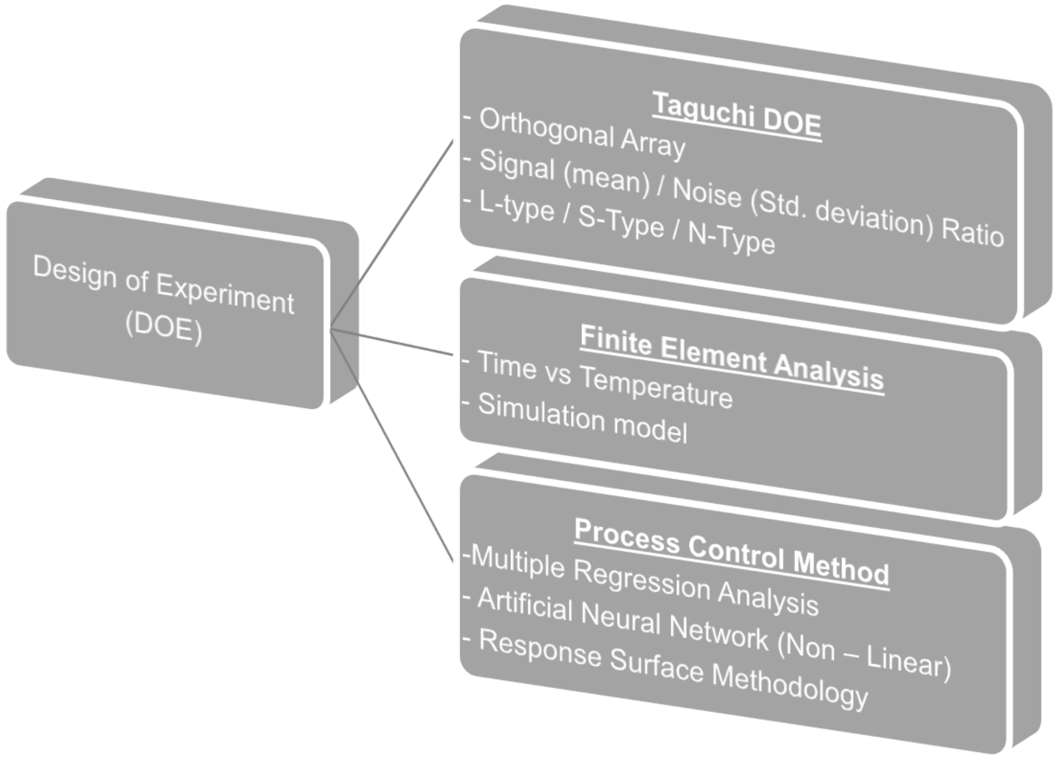


Figure 14: Design of experiments on a different methodology

Equation 18 and 19 derived by Douglas C. Montgomery in statistical quality control for the quadratic model for the thesis [33];

$$Y\ (FCAW) = \beta_0 + \beta_1\ A + \beta_2\ F + \beta_3\ HI + \beta_4\ CTWD + \beta_{11}\ A^2 + \beta_{22}\ F^2 + \beta_{33}\ HI^2 + \beta_{12}\ A{*}F + \beta_{13}\ A{*}HI + \beta_{23}\ F{*}HI + \beta_{34}\ HI{*}CTWD + \beta_{14}\ A{*}CTWD) + \beta_{24}\ F{*}CTWD. \quad (18)$$

$$= \beta_0 + \beta_1\ (current) + \beta_2\ (wire\ feed) + \beta_3\ (Heat\text{-}input) + \beta_4\ (CTWD) + \beta_{11}\ (current^2) + \beta_{22}\ (wire\ feed^2) + \beta_{33}\ (heat\text{-}input^2) + \beta_{12}\ (current{*}wire\ feed) + \beta_{13}\ (current{*}heat\text{-}input) + \beta_{23}\ (wire \quad (19)$$

feed*heat-input) + β_{34} (heat-input*CTWD) + β_{14} (current*CTWD) + β_{24} (wire feed*CTWD)

In Equations 18 and 19; author designates betas as the coefficient of linear, quadratic and interaction of input V (voltage), F (wire feed), S (travel speed), A (current), HI (Heat Input) and CTWD (cup to workpiece distance). The β_0 is the intercept term whereas β_1, β_2, β_3, β_4 and β_{11}, β_{22}, β_{33} β_{34}, β_{14}, β_{24} are the linear terms and interaction between variables terms respectively [33].

The welding factors classify as either continuous value or as categorical values. The author has selected continuous type of factors instead of the categorical type with minimum and maximum value because the FCAW factor's values frequently fluctuate due to welding in the temporary welding shop. Design of experiment executed by selecting current (A), wire feed (mm); heat Input (KJ/mm) and electrode extension (mm) as continuously controllable factors with low and high values as defined in Table 13 and Table 14. These controllable factor's effects studied on four responses such as bead width (mm), weld reinforcement height (mm), weldment hardness (HB) and deposition rate (lb/hr). Each response assigned with minimum and maximum values which obtained from the design condition for ASME B31.3 process piping for non-sour and non-lethal service, Moreover, are mentioned in Table 13. The response's results are studied and analysed on mean values basis and target to minimise the mean of hardness and maximise the mean of deposition rate, reinforcement height, and bead width [34].

Table 13: Defining of responses to be varied for FCAW

Name	Units	Analyse	Objective	Impact	Sensitivity	Low	High
Hardness	HV	Mean	Minimize	3.0	Medium	160.0	230.0
Deposition Rate	lb/hr	Mean	Maximize	3.0	Medium	10.0	16.0
Bead Width	mm	Mean	Maximize	3.0	Medium	8.0	14.0
Reinforcement	mm	Mean	Maximize	3.0	Medium	2.0	4.0

Table 14: Defining of controllable factors to be measured for FCAW

Name	Units	Type	Role	Low	High
A:Current	Amp	Continuous	Controllable	90.0	330.0
B:Wire Feed	mm/min	Continuous	Controllable	135.0	235.0
C:Heat input	kJ/mm	Continuous	Controllable	12.0	20.0
D:CTWD	mm	Continuous	Controllable	12.0	25.0

Design of experiment's run and the model was established by response surface methodology which is used to refine the model after determination of important controllable factors using central composite design. CCD is used because of its fit the quadratic model with subsequent experiments. The design is rotatable in composite design because it provides constant prediction at all points that are equidistant from the design centre which placed in last. The star points in rotatable centre composite design are the distance of each axial point. The design matrix for a central composite design experiment involving *k* factors derived from a matrix, d, containing the following three different parts corresponding to the three types of experimental runs [33], [34] ;

1. The matrix F obtained from the factorial experiment. The factor (F_1, F_2,..F_n) levels are scaled so that its entries are coded as +1 (maximum) and −1 (minimum) as shown in Figure 15;

F =

F1	F2	F3	F4
-	-	-	-
+	-	-	-
-	+	-	-
+	+	-	-
-	-	+	-
+	-	+	-
-	+	+	-
+	+	+	-
-	-	-	+
+	-	-	+
-	+	-	+
+	+	-	+
-	-	+	+
+	-	+	+
-	+	+	+
+	+	+	+

Figure 15: 2^k full factorial design matrix ("+" as maximum, "-" as a minimum)

2. The matrix C from the centre points denoted in coded variables as (0,0,0,0) middle of maximum and minimum value, where there are k zeros.

3. A matrix E compromised on axial points having 2k rows. Each factor sequentially placed at ± α (Stars Points), and all other factors are at zero. Center points are augmented with star points as shown in Figure 16;

$$\mathbf{E} = \begin{bmatrix} \alpha & 0 & 0 & \cdots & \cdots & \cdots & 0 \\ -\alpha & 0 & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & \alpha & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & -\alpha & 0 & \cdots & \cdots & \cdots & 0 \\ \vdots & & & & & & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \cdots & \alpha \\ 0 & 0 & 0 & 0 & \cdots & \cdots & -\alpha \end{bmatrix}$$

Figure 16: Axial/start points matrix of CCD for FCAW

Therefore, the complete central composite design model shows in Figure 17 [33];

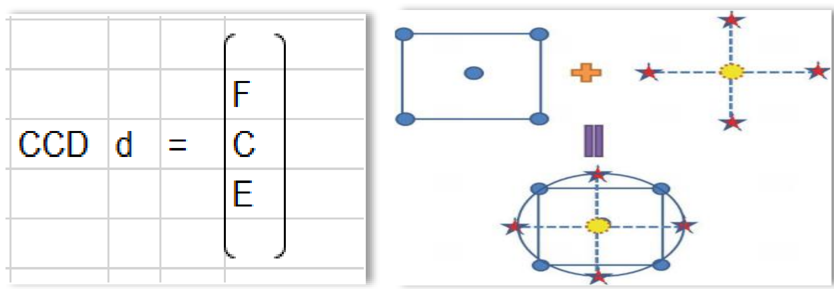


Figure 17: Complete CCD matrix for FCAW

Total 36 runs designed with 12 centre points per block. The DOE summarised in Table 15. Statistical process control software "The statgraphics Centurion" was used to run the design of experiments [34].

The quadratic model of factors interaction used and Table 16 is the statistical data collected from massive data points of the mobile welding shop, 32 runs are collected, and responses of each run measured from actual testing in a mechanical laboratory. Missing data points precisely welded on parameters advised by DOE matrix.

Table 15: Design of experiments for an FCAW

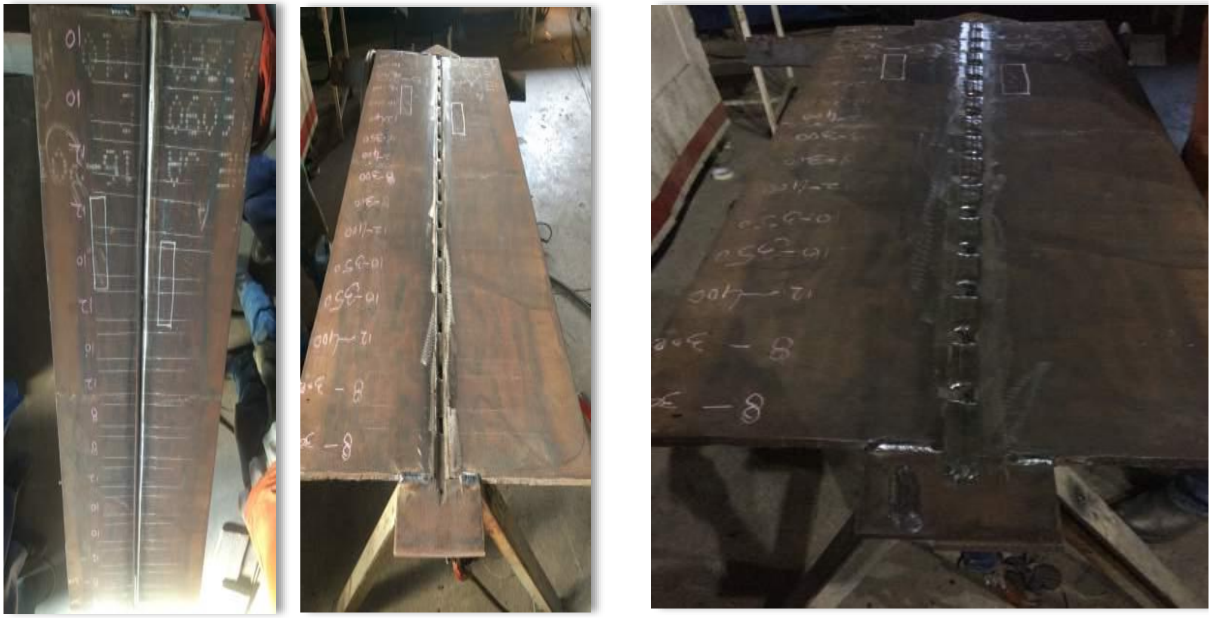
Type of	**Design**	**CenterPoint**	**CenterPoint**	**Design is**	**Total**
Factors	Type	Per Block	Placement	Randomised	Runs
Process	Central composite design: 2^4 + star	12	Last	Yes	Total Run= 16+12+8 = 36 Total Corner Points = 2^K = 2^4 = 16 Total Center Points = 12 Total Star Points = 2xn=2x4=8

Start points for Table 15 calculated by Equation 20;

$$\alpha = \frac{2^{k-1} \times \text{No. of Corner Points}}{\text{No. of Axial Points}} \qquad (20)$$

Figure 18 the photos of the test coupons that were welded to gather the data for missing data points; To fulfil the design of experiments matrix large pool of data points are selected, and these data points are published on ResearchGate having DOI as 10.13140/RG.2.2.18336.89602 (https://www.researchgate.net/publication/325103129) with the title of "Field Data for FCAW variables and responses for process optimisation studies". In addition to this data pool [35].

We have welded 15 number of test coupon for that combination which was not available in the data pool.



(a) Photos of the first set of test coupons

(b) (FCAW welding setup used for the welding of the first set of test coupons

(c) Photos of 2nd set of test coupons

Figure 18: Coupons welded to gather the missing data points for FCAW

Refer to Table 16 for a specific combination of controllable welding factors used in the thesis.

Table 16: Design of experiments for FCAW

	Controllable factors				**Responses received from welded work Pieces**			
	F1	**F2**	**F3**	**F4**	**R1**	**R2**	**R3**	**R4**
Run	Current	Wire Feed	Heat input	CTWD	Hardness of Weldment	Deposition Rate	Bead Width	Reinforcement
Unit	Amp	mm/min	KJ/mm	mm	HV	lb/hr	mm	mm
1	330	235	12	12	175.5	11	10	2
2	330	235	20	12	190	15	12	3
3	90	235	20	12	171	13	9	4
4	210	185	16	20	188	12	10	3
5	90	135	20	12	162	13	8	4
6	210	285	16	18.5	195	12	10	3
7	210	185	24	18.5	198	14	11	3.5
8	90	135	20	25	168	13	8	4
9	300	185	16	18.5	210	13	13	2.8
10	450	185	16	18.5	205	14	10	3
11	90	135	12	12	165	10	9	2.5
12	90	235	20	25	175	13	9	3
13	210	185	16	20	181	12	12	3.5
14	210	185	16	18.5	177	12	11	3

15	330	235	20	25	225	15	14	3
16	330	135	12	12	185	12	11	4
17	330	135	20	12	212	14	12	3
18	330	135	12	25	165	11	10	3
19	90	135	12	25	166	11	10	2.5
20	90	235	12	12	178	10	9	2.5
21	210	185	12	18.5	187	10	12	2
22	90	235	12	25	178	11	10	2.5
23	330	235	12	25	180	12	13	3.5
24	330	135	20	25	225	15	12	4
25	210	185	16	18.5	181	11	11	3
26	210	185	16	18.5	177	11	11	3
27	210	185	16	18.5	181	11	11	3
28	210	185	16	18.5	177	12	11	3
29	210	185	16	18.5	181	11	11	3
30	210	185	16	18.5	177	11	11	3
31	210	185	16	18.5	181	11	11	3
32	210	185	16	18.5	177	11	11	3
33	210	185	16	18.5	181	12	11	3
34	210	185	16	18.5	177	11	11	3
35	210	185	16	18.5	185	11	11	3
36	210	185	16	18.5	180	11	11	3

By deploying design of experiment on FCAW, all factors (F1, F2, F3 and F4) and responses (R1, R2, R3 and R4) value tabulated in Table 16 and after that ANOVA is used to segregate between significant and non-significant factors about responses target values.

4.3 ANALYSIS OF VARIANCE "ANOVA."

ANOVA is known as analysis of variance which is a statistical model and is used to analyse the variance in a large group of data. By applying the ANOVA models, the statistical significance of data is extracted resulting the less chance of type-I error. For thesis probability (P-Value) is set maximum 0.05% at 95% confidence level and it means all variables are having output result less than 0.05% P-value will be considered as a significant variable for the welding process under the circumstances. After welding Data matrix created through CCD of RSM, then data is passed through a significance test. Since the observed response values and expected response values are different, it means, there are following two possibilities [33] ;

1. It happened only by chance (5%)
2. It happened by manipulation of controllable variables. (95%)

Therefore, we start from Null Hypo-thesis, mean that the obtained variables do not bear any relation or significance with the responses and to check the null hypothesis rejection or correctness, P-Value must be calculated. If the P-value is less than alpha value, then it will reject the null hypothesis P-Value calculated from Equation 21 [33];

$$\text{P-Value} = \text{F.DIST (F-ratio, DF1, DF2, FALSE)} \qquad (21)$$

Degrees of freedom is a measure of the amount of variability involved in the research. The Equation for degrees of freedom is degrees of freedom = n-1, where "n" is the number of categories or variables analysed in your experiment. As per formula DOF=3 but we considered most stringent value, i.e. 1. Based on the ANOVA the analysis of variance is calculated for each response and is explained in detail, refer below to Table 17 for hardness,

Table 18 for deposition rate, Table 19 for bead width and Table 20 for reinforcement height; Graphical representation of analysis of variances for each response is also showed which determines how far out from the null hypothesis value. Samples mean of each response are calculated and plotted on variance Table and noticed that if sample mean falls within the critical region then the data indicates statistically significant at the 0.05 level, refer to Figure 19 explain on general perspective and Figure 21, 22, 23, 24 are specific to each response whereas Figure 20 illustrates the regression analysis .

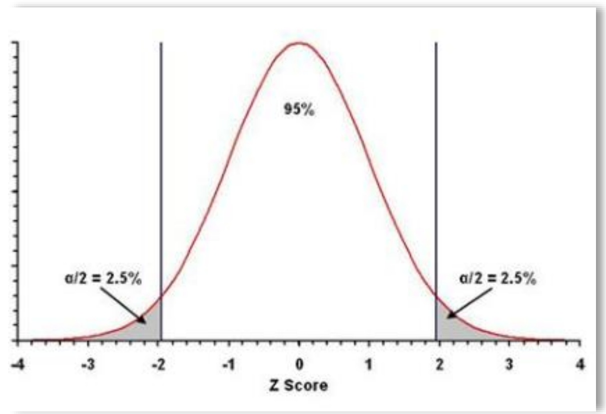


Figure 19: Data distribution for 0.05 significant level

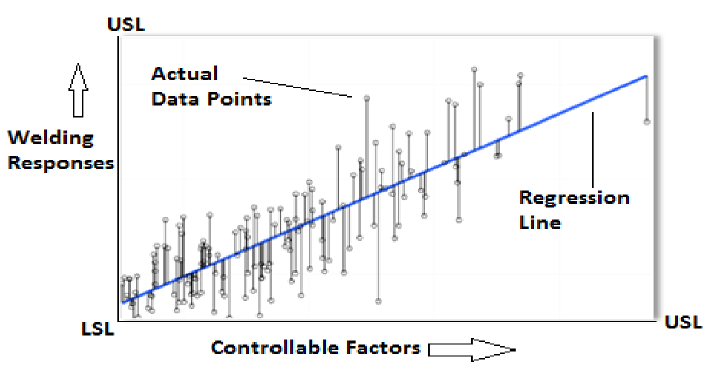


Figure 20: Regression analysis between response and factors

4.3.1 VARIANCE'S ANALYSIS OF HARDNESS (R1) FOR FCAW

The variability in hardness obtained by ANOVA Table 17 and is mentioned separately for all effects. By comparison between mean square with experimental error (estimated), the statistical significance calculated. If the P-value is less than 0.05 then the response or their interaction are significant, and, in our analysis, we found four cases where P-value is less than 0.05, and it is the indicating factor for significantly different from 0 at 95.0% confidence level [36].

Table 17: Variance's analysis of hardness (R1) for FCAW

Factors/ interaction	**Sum of Squares**	**Degree of freedom**	**Mean Square = Sum of Square / DOF**	**F-Ratio = Mean Square / Total Error**	**P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)**
A:Current	2619.0604	1	2619.0604	51.51	0.0000
B:Wire Feed	37.904121	1	37.904121	0.75	0.3977
C:Heat input	985.04658	1	985.04658	19.37	0.0002
D:CTWD	124.98295	1	124.98295	2.46	0.1319
AA	0.18639344	1	0.18639344	0.00	0.9523
AB	206.64063	1	206.64063	4.06	0.0568
AC	1550.3906	1	1550.3906	30.49	0.0000
AD	28.890625	1	28.890625	0.57	0.4593
BB	79.676263	1	79.676263	1.57	0.2244
BC	83.265625	1	83.265625	1.64	0.2146
BD	118.26563	1	118.26563	2.33	0.1421
CC	16.460496	1	16.460496	0.32	0.5754
CD	328.51563	1	328.51563	6.46	0.0190

DD	28.868497	1	28.868497	0.57	0.4595
Total error	1067.6805	21	50.841929		
Total (corr.)	8201.6875	35			

R-squared and adjusted R-squared calculated with Equation 22 and 23;

$$\text{R-Squared} = 1 - \frac{(\text{Sum of Square} - \text{Sum of the square of Error})}{\text{`Total Sum of Square}} \quad (22)$$

$$\text{Adjusted R-Squared due to Degree of freedom} = 1 - \frac{(1\text{-R2}) \; . \; (n\text{-}1)}{n\text{-}k\text{-}1} \quad (23)$$

Value of R-Squared is calculated to explain the fitted in the model which is 86.982185% of the variability in hardness. The value of R-squared adjusted as 78.303642% and the value is most suitable for comparing models with a different independent response. In the same way, the standard error is 7.13 and MAE are 3.88 which is the average value of the residuals [34].

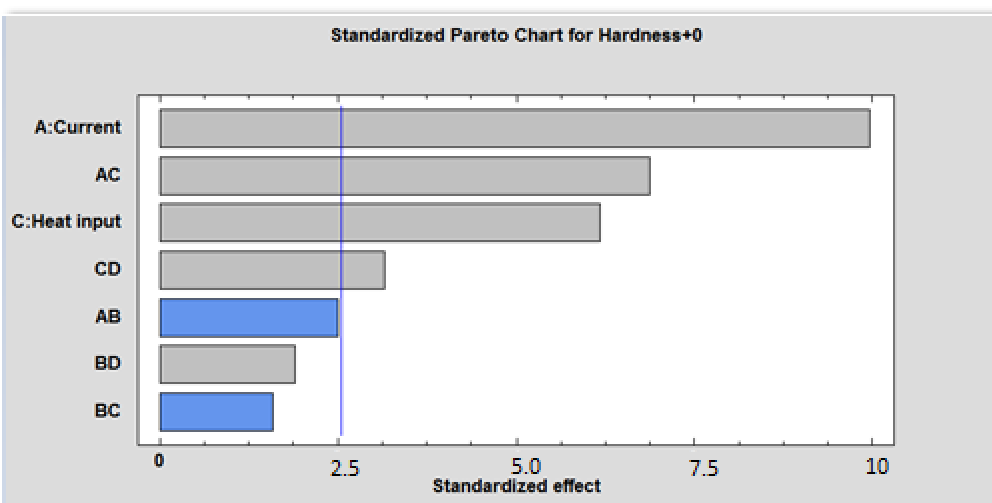


Figure 21: Standardized Pareto chart of hardness (R1) for FCAW

Based on analysis of variance through ANOVA, the significant controllable factors are identified and then plot against the standardised effect. Figure 21 shows that current, heat input, the quadratic effect of current and heat input has a significant effect on hardness value whereas the other factors ignored from the Pareto chart and the further process. Figure 21 shows only factors with p-value 0.2%, but we considered factors whose P value are less than 0.05% [34].

4.3.2 VARIANCE'S ANALYSIS OF DEPOSITION RATE (R2) FOR FCAW

In an analysis of variance for deposition rate as tabulated in Table 18, we have found four current interaction, heat input and AA and DD effects the deposition because P-values is smaller than 0.05, at the 95.0% confidence level [34].

Table 18: Variance's analysis of deposition rate (R2) for FCAW

Factors/ interaction	**Sum of Squares**	**Degree of freedom**	**Mean Square = Sum of Square / DOF**	**F-Ratio = Mean Square / Total Error**	**P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)**
A: Current	8.3005897	1	8.3005897	29.85	0.0000
B: Wire Feed	0.066144076	1	0.066144076	0.24	0.6308
C: Heat input	36.882212	1	36.882212	132.63	0.0000
D: CTWD	0.66349255	1	0.66349255	2.39	0.1374
AA	1.2959405	1	1.2959405	4.66	0.0426
AB	0.0625	1	0.0625	0.22	0.6403
AC	0.5625	1	0.5625	2.02	0.1696
AD	0.0625	1	0.0625	0.22	0.6403

BB	0.17527193	1	0.17527193	0.63	0.4361
BC	0.0625	1	0.0625	0.22	0.6403
BD	0.0625	1	0.0625	0.22	0.6403
CC	0.042469031	1	0.042469031	0.15	0.6999
CD	0.0625	1	0.0625	0.22	0.6403
DD	1.5727648	1	1.5727648	5.66	0.0270
Total error	5.8396424	21	0.27807821		
Total (corr.)	70.0	35			

The value of R-Squared is 91.6%, and the adjusted R-squared value is 86.09 %, and standard error is 0.5, and the mean absolute error is 0.343.

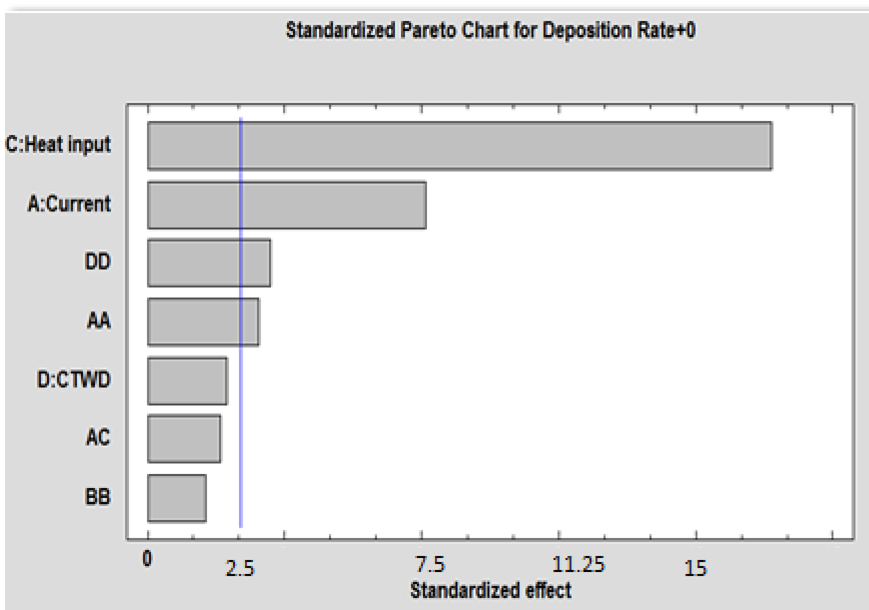


Figure 22: Standardized Pareto chart of deposition rate (R2) for FCAW

Based on the analysis of variance through ANOVA, the significant controllable factors are identified and then plot against the standardised effect. Figure 22 shows that current, heat input, the quadratic effect of current and heat input has a significant effect on the deposition rate whereas the other factors ignored from the Pareto chart and the further process. Figure 22 shows only factors with p-value 0.4%, but we considered factors whose P value are less than 0.05% [34].

4.3.3 VARIANCE'S ANALYSIS OF BEAD WIDTH (R3) FOR FCAW

In an analysis of variance for bead width as tabulated in Table 19, we have found seven current interaction, wire feed, AA, AC, BB, BD et cetera effects the bead width because P-values is smaller than 0.05, at the 95.0% confidence level. The value of R-Squared is 86.12%, and adjusted R-squared value is 76.87 %, and standard error of Est is 0.6, and the mean absolute error is 0.346 [34].

Table 19: Variance's analysis of bead width (R3) for FCAW

Factors/ interaction	**Sum of Squares**	**Degree of freedom**	**Mean Square = Sum of Square / DOF**	**F-Ratio = Mean Square / Total Error**	**P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)**
A:Current	32.399373	1	32.399373	80.72	0.0000
B:Wire Feed	2.2410869	1	2.2410869	5.58	0.0279
C:Heat input	0.026391575	1	0.026391575	0.07	0.8001
D:CTWD	2.1845427	1	2.1845427	5.44	0.0297
AA	10.67738	1	10.67738	26.60	0.0000
AB	0.25	1	0.25	0.62	0.4388
AC	6.25	1	6.25	15.57	0.0007
AD	0.25	1	0.25	0.62	0.4388
BB	2.6191071	1	2.6191071	6.53	0.0185
BC	0.25	1	0.25	0.62	0.4388

BD	2.25	1	2.25	5.61	0.0276
CC	0.0021814827	1	0.0021814827	0.01	0.9419
CD	0.25	1	0.25	0.62	0.4388
DD	1.4653593	1	1.4653593	3.65	0.0698
Total error	8.4291227	21	0.4013868		
Total (corr.)	60.75	35			

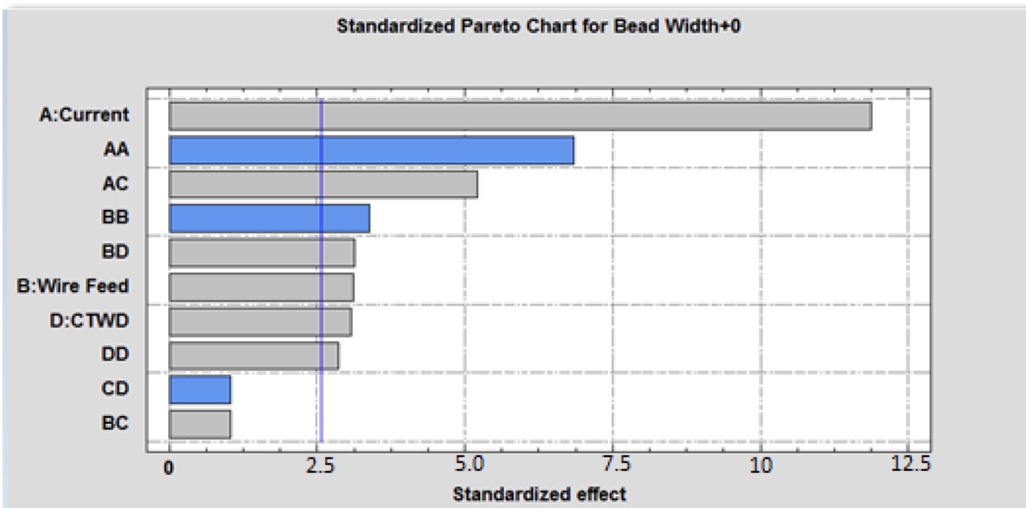


Figure 23: Standardized Pareto chart of bead width (R3) for FCAW

Base on the analysis of variance through ANOVA, the significant controllable factors are identified and then plotted against the standardised effect. Figure 23 shows that current, wire feed and CTWD and their combined interaction have significant effect on bead width. Whereas the other factors ignored from the Pareto chart and the further process [34].

4.3.4 VARIANCE'S ANALYSIS OF REINFORCEMENT (R4) FOR FCAW

In an analysis of variance for reinforcement height as tabulated in Table 20, we have found three current interaction, wire feed and AC effects the reinforcement height because P-values is smaller than 0.05, at the 95.0% confidence level. The value of R-Squared is 66.28%, and adjusted R-squared value is 43.80 %, and standard error of EST is 0.3 and means the absolute error is 0.18288 [34].

Table 20: Variance's analysis of reinforcement (R4) for FCAW

Factors/ interaction	**Sum of Squares**	**Degree of freedom**	**Mean Square = Sum of Square / DOF**	**F-Ratio = Mean Square / Total Error**	**P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)**
A: Current	0.011056323	1	0.011056323	0.08	0.7805
B: Wire Feed	0.76015143	1	0.76015143	5.48	0.0292
C: Heat input	2.7666318	1	2.7666318	19.94	0.0002
D: CTWD	0.023376017	1	0.023376017	0.17	0.6856
AA	0.0049954797	1	0.0049954797	0.04	0.8513
AB	0.140625	1	0.140625	1.01	0.3256
AC	1.265625	1	1.265625	9.12	0.0065
AD	0.390625	1	0.390625	2.81	0.1082
BB	0.14519441	1	0.14519441	1.05	0.3180
BC	0.015625	1	0.015625	0.11	0.7405
BD	0.015625	1	0.015625	0.11	0.7405
CC	0.14045144	1	0.14045144	1.01	0.3258
CD	0.015625	1	0.015625	0.11	0.7405
DD	0.1089928	1	0.1089928	0.79	0.3855
Total error	2.9141605	21	0.13876955		
Total (corr.)	8.6430556	35			

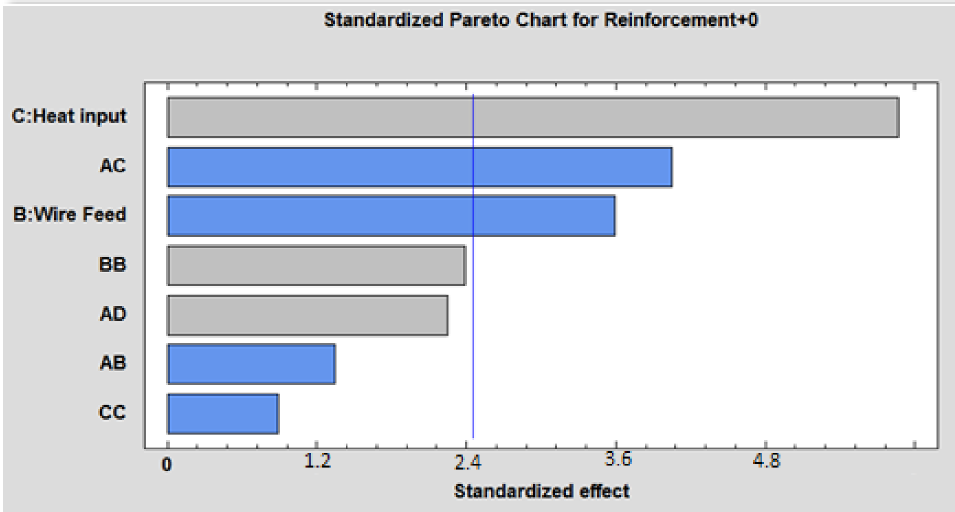


Figure 24: Standardized Pareto chart of reinforcement height (R4) for FCAW

Based on analysis of variance through ANOVA, the significant controllable factors are identified and then plotted against the standardised effect. Figure 24 shows that current, wire feed and AC have a significant effect on reinforcement height whereas the other factors ignored from the Pareto chart and the further process.

Since we have executed the design of experiment for FCAW and then segregation of significant and non-significant factors is also done. Now the optimisation will be carried out in chapter 6. The optimisation will be carried out through desirability function to attain the weld joint with hardness smallest the best, deposition rate the more significant the best et cetera [34] [37].

CHAPTER 5

BOX-BEHNKEN DESIGN OF QUADRATIC MODEL FOR GAS METAL ARC WELDING (GMAW) AND ANALYSIS OF VARIANCE (ANOVA)

Chapter four outlined the complete design of experiments for GMAW and in the end, the developed model is obtained which is further used for the optimisation

5.1 DOE FOR GMAW

As discussed in chapter 4 about basic of the design of experiments for FCAW, in this chapter design of the experiment is developed for GMAW to find the solution of welding field issues.

To fulfil the design of experiments matrix large pool of data points are selected, and these data points are published on ResearchGate having DOI as 10.13140/RG.2.2.29164.00644 (https://www.researchgate.net/publication/329863368) with the title of "Field Data for GMAW variables and responses for process optimisation Studies". In addition to this data pool, we have welded 17 numbers of test coupon for that combination which was not available in the data pool [38] . Refer to Table 21 and 22 for a specific combination of controllable welding factors used in the thesis. Figure 25 shows the Photos of GMAW setup used for the thesis;

Figure 25: GMAW welding setup used for actual welding

GMAW's design of the experiment done by selecting voltage (V), welding consumable feed speed (mm), and travel speed (cm/mm) as continuously controllable factors with low and high values as defined in Table 21. These controllable factor's effects studied on four responses such as weld bead (mm), bead reinforcement height (mm), penetration depth (mm) and deposition efficiency (%). Each response assigned with minimum and maximum values which are obtained from the design condition for the ASME B31.3 process piping for non-sour and non-lethal service. The response's results are studied and analysed on mean values basis and target to maximise the mean of the depth of penetration, deposition efficiency. The quantitative relation between responses and factors in term of RSM can express as per Equation 24 derived by Douglas C. Montgomery in statistical quality control [33];

$$Y = f\,(\text{Voltage},\ \text{wire feed},\ \text{travel speed}) \qquad (24)$$

Whereas Y is the responses and V, F and S are the controllable factors. The system behaviour will be obtained through quadric model or by higher order polynomial model which is developed by the least square method by considering the interaction of factors to maximise or minimise the response variables, below is Equation 25 derived by Douglas C. Montgomery in statistical quality control for the quadratic model for the thesis [33];

$$\mathbf{Y} = \beta_0 + \beta_1 \text{ (Voltage)} + \beta_2 \text{ (wire feed)} + \beta_3 \text{ (travel speed)} + \beta_{11} \text{ (volatge}^2\text{)} + \beta_{22} \text{ (wire feed}^2\text{)} + \beta_{33} \text{ (travel speed}^2\text{)} + \beta_{12} \text{ (voltage*wire feed)} + \beta_{13} \text{ (voltage*travel speed)} + \beta_{23} \text{ (wire feed*travel speed)} \quad (25)$$

In Equation 25; author designates betas as the coefficient of linear, quadratic and interaction of input V, F, T. The β_0 is the intercept term whereas β_1, β_2, β_3 and β_{11}, β_{22}, β_{33} are the linear terms and interaction between variables terms respectively.

The DOE parameters tabulated in Table 21 and 22 [34].

Table 21: Defining of responses to be varied for GMAW

Name	**Units**	**Analyse**	**Goal**	**Impact**	**Sensitivity**	**Low**	**High**
Depth of Penetration	mm	Mean	Maximize	3.0	Medium	4.5	6.0
Deposition Efficiency	%	Mean	Maximize	3.0	Medium	55.6	93.4
Bead Width	mm	Mean	Maximize	3.0	Medium	6.5	8.0
Bead Reinforcement	mm	Mean	Maximize	3.0	Medium	0.7	3.0

Table 22: Defining of controllable factors to be measured for GMAW

Name	**Units**	**Type**	**Role**	**Low**	**High**
A:Welding Voltage	V	Continuous	Controllable	29.0	34.2
B: Wire Feed Speed	inch	Continuous	Controllable	3.9	9.7
C:Welding Speed	mm/min	Continuous	Controllable	50.0	70.0

Design of the experiment's run and the model established by Box-Behnken design which was developed by George E.P.Box. Box-Behnken is one of the experimental strategies for RSM where each factor placed at equally distributed values on at least three levels, and it fits on the quadratic model the design is equidistant from the design centre which placed in last. Total 30 runs designed with three centre points per block. Box-Behnken's DOE tabulated in Table 23 [34];

Table 23: Design of experiments for the GMAW

Type of	**Design**	**Center points**	**CenterPoint**	**Design is**	**Number of**	**Total**	**Total**
Factors	Type	Per Block	Placement	Randomised	Replicates	Runs	Blocks
Process	Box-Behnken design	3	Last	Yes	1	30	2

The welding conducted on 10mm ASTM A 36/53 material with single bevel angle. Bevel angle checked with dye penetrant testing for any possible defects like crack. GMAW machine of model MAXI 505 used for welding whereas reinforcement measured by using Cambridge welding gauge. Figure 26 the photos of the test coupons that were welded to gather the data for missing data points of GMAW;

(a) Joint preparation for GMAW test coupons

(b) Photos for GMAW test coupons

Figure 26: Coupons welded to gather the missing data points for GMAW

By deploying the design of experiment on GMAW, all factors (F1, F2 and F3) and responses (R1, R2, R3 and R4) value tabulated in Table 24. Statistical process control software "The statgraphics centurion" was used to run the design of experiments and to get the DOE matrix [34].

Table 24: Data Matrix of DOE for GMAW

	FACTORS			RESPONSES			
	F1	**F2**	**F3**	**R1**	**R2**	**R3**	**R4**
Sr	Voltage (V)	Wire Feed	Travel Speed	Depth of Penetration (mm)	Deposition Efficiency (%)	Bead Width (mm)	Weld Reinforcement (mm)
1	29	6.8	50.0	5	55.6	6.50	0.7
2	34.2	6.8	70.0	6	91.6	6.50	2.0
3	29	9.7	60.0	5	90	6.00	2.0
4	31.6	3.9	50.0	5.5	77	8.50	3.0
5	29	3.9	70.0	5	77	8.00	2.5

6	31.6	3.9	50.0	4.5	56	6.50	0.8
7	34.2	6.8	70.0	5.5	92.5	6.50	2.2
8	34.2	9.7	60.0	6	92	6.00	2.2
9	31.6	9.7	50.0	6.5	80	8.00	3.0
10	31.6	9.7	60.0	5.3	92.3	6.50	2.0
11	34.2	3.9	70.0	5.2	92.1	6.40	2.0
12	29	6.8	50.0	5.3	92.3	6.50	2.0
13	31.6	6.8	60.0	5	92.2	6.50	2.0
14	34.2	9.7	70.0	5.3	88.7	7.0	3.0
15	31.6	3.9	50.0	5.6	90.2	7.7	2.9
16	31.6	6.8	60.0	5.3	90.7	6.3	2.5
17	34.2	3.9	70.0	5.3	88.6	7.8	3.1
18	29	6.8	50.0	6.0	94.7	7.3	2.7
19	31.6	9.7	60.0	6.1	94.0	9.4	2.9
20	34.2	9.7	70.0	6.1	94.6	6.1	2.5
21	31.6	3.9	50.0	5.7	93.0	8.5	2.9
22	31.6	6.8	60.0	5.2	88.3	6.3	2.9
23	34.2	6.8	70.0	5.2	87.7	7.0	3.0
24	29	9.7	50.0	5.2	89.1	6.3	2.5
25	31.6	3.9	60.0	5.4	89.4	7.7	2.9
26	34.2	6.8	70.0	5.8	93.3	7.3	2.7
27	29	3.9	50.0	6.3	96.5	9.6	3.4
28	31.6	6.8	60.0	5.9	95.2	6.6	2.6
29	34.2	9.7	70.0	6.3	98.9	10.5	2.6
30	31.6	3.9	50.0	5.6	91.7	6.6	2.8

After DOE execution, ANOVA is used to segregate between significant and non-significant factors regarding responses target values.

5.2 ANALYSIS OF VARIANCE “ANOVA” for GMAW

ANOVA was conducted to investigate the controllable factor’s influences on measured responses then the standardised Pareto chart is drawn for each response associated with significant factors. The analysis of variance is calculated for each of response and explained in detail, refer below to Table 25 for the depth of penetration, Table 26 for deposition efficiency, Table 27 for bead width and Table 28 for weld reinforcement height. ANOVA graphical representation was done as discussed in previous section 4.3 [36].

5.2.1 ANOVA FOR DEPTH OF PENETRATION – R1 FOR GMAW

Table 25 is the variance analysis known as “ANOVA” where statistical significance calculated by associating the experimental error with a mean square. The mean square value obtained by computing the variability in Square root (DOP) into a distinct run for each of the effects. In author occasion, some interactions of factors have not P-values less than 0.05 which confirmed that these interactions are meaningfully diverse from “0” at the 95.0% confidence level. The R-Squared calculation shows that the model as fitted illuminates 59.7% of the variability in Square-Root of depth of penetration [36].

Table 25: Variance’s analysis for SQRT of the depth of penetration (R1) for GMAW

Factors/ interaction	Sum of Squares	Degree of freedom	Mean Square = Sum of Square / DOF	F-Ratio = Mean Square	P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)

				/ Total Error	
A: Welding Voltage	0.0330452	1	0.0330452	1.73	0.02799
B: Wire Feed Speed	0.0384051	1	0.0384051	2.01	0.02512
C: Welding Speed	0.0113129	1	0.0113129	0.59	0.04975
AA	0.00000229293	1	0.00000229293	0.00	0.9919
AB	0.00715199	1	0.00715199	0.37	0.05838
AC	0.00036437	1	0.00036437	0.02	0.8989
BB	0.0000164209	1	0.0000164209	0.00	0.9784
BC	0.000137468	1	0.000137468	0.01	0.9377
CC	0.0020654	1	0.0020654	0.11	0.7639
Total error	0.0572911	3	0.019097		
Total (corr.)	0.150612	12			

The adjusted R-squared calculation is 39.55 %. The standard error of the calculation indicates 0.0871038. The mean absolute error of 0.0590065 is the average value of the residuals.

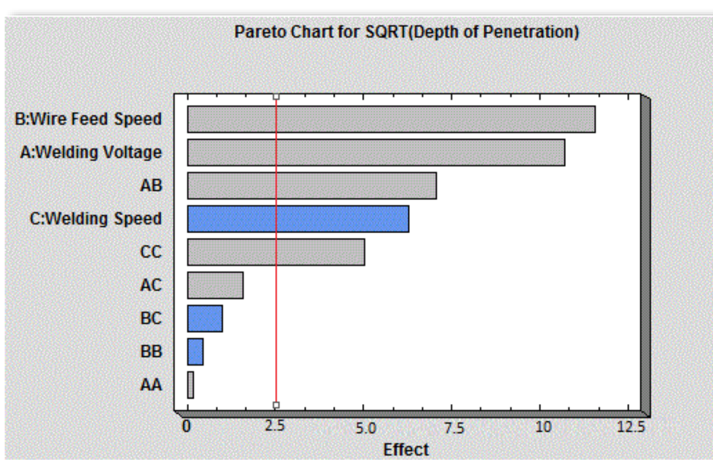


Figure 27: Pareto chart for SQRT of the depth of penetration (R1) for GMAW

Based on analysis of variance through ANOVA, the significant controllable factors are identified and then plotted against the standardised effect. Figure 27 shows that Wire Feed, welding voltage and their quadratic effect have a significant effect on depth of penetration as compared to other factors [36].

5.2.2 ANOVA OF DEPOSITION EFFICIENCY – R2 FOR GMAW

Table 26 is the variance analysis known as "ANOVA" where statistical significance calculated by associating the experimental error with a mean square. The mean square value obtained by computing the variability in Square-Root (DOP) into a distinct run for each of the effects. In author occasion, some interactions of factors have not P-values less than 0.05 which confirmed that these interactions are meaningfully diverse from "0" at the 95.0% confidence level [36].

Table 26: Variance's analysis for SQRT of deposition efficiency (R2) for GMAW

Factors/ interaction	**Sum of Squares**	**Degree of freedom**	**Mean Square = Sum of Square / DOF**	**F-Ratio = Mean Square / Total Error**	**P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)**
A: Welding Voltage	1.16387	1	1.16387	2.45	0.02158
B: Wire Feed Speed	1.12495	1	1.12495	2.36	0.02217
C: Welding Speed	0.272031	1	0.272031	0.57	0.05045
AA	0.00838265	1	0.00838265	0.02	0.9028
AB	0.128551	1	0.128551	0.27	0.6391

AC	1.20742	1	1.20742	2.54	0.02094
BB	0.205795	1	0.205795	0.43	0.5577
BC	0.95518	1	0.95518	2.01	0.02515
CC	0.821663	1	0.821663	1.73	0.02802
Total error	1.42735	3	0.475783		
Total (corr.)	7.44221	12			

The R-Squared calculation shows that the model as fitted illuminates 80.82% of the variability in Square-Root (Depth of Penetration). The adjusted R-squared calculation is 23.22 %. The standard error of the calculation shows 0.689771 for the standard deviation of the residuals. The mean absolute error of 0.271215 is the average value of the residuals [36].

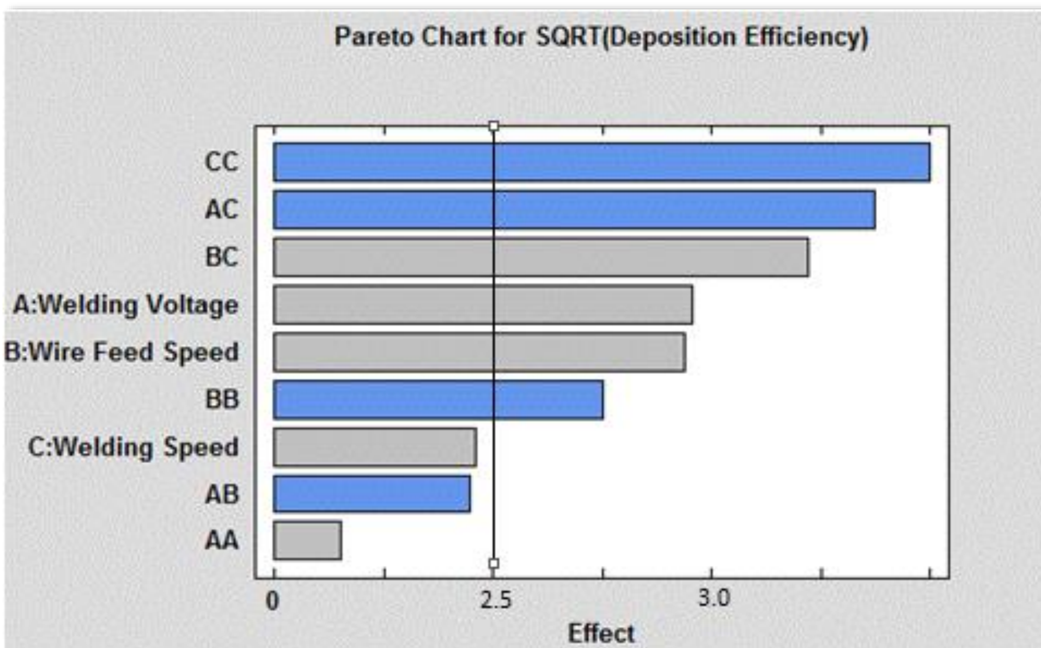


Figure 28: Pareto chart for SQRT (deposition efficiency – R2) for GMAW

Based on analysis of variance through ANOVA, the significant controllable factors are identified and then plotted against the standardised effect. Figure 28 shows that quadric effect of Welding voltage and wire feed and wire feed and welding speed have a significant effect on deposition efficiency as compared to other factors [34] , [36] .

5.2.3 ANOVA OF BEAD WIDTH – R3 FOR GMAW

Table 27 shows he R-Squared calculation that the model as fitted illuminates 70.3999% of the variability in Square root (Depth of Penetration). The adjusted R-squared calculation is 0.0 %, which is appropriate for analysing the matrix with a dissimilar number of independent variables — the estimated standard error for the standard deviation of the residuals to be 0.163756.

The mean absolute error of 0.0639226is the average value of the residuals.

Table 27: Variance's analysis for SQRT of bead width (R3) for GMAW

Factors/ interaction	**Sum of Squares**	**Degree of freedom**	**Mean Square = Sum of Square / DOF**	**F-Ratio = Mean Square / Total Error**	**P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)**
A: Welding Voltage	0.0111456	1	0.0111456	0.42	0.05650
B: Wire Feed Speed	0.037308	1	0.037308	1.39	0.03232
C: Welding Speed	0.0519844	1	0.0519844	1.94	0.02581
AA	0.0122513	1	0.0122513	0.46	0.5475
AB	0.0222912	1	0.0222912	0.83	0.4291
AC	0.0	1	0.0	0.00	0.0100

BB	0.0177043	1	0.0177043	0.66	0.4760
BC	0.00189437	1	0.00189437	0.07	0.05076
CC	0.0122513	1	0.0122513	0.46	0.05475
Total error	0.0804485	3	0.0268162		
Total (corr.)	0.271784	12			

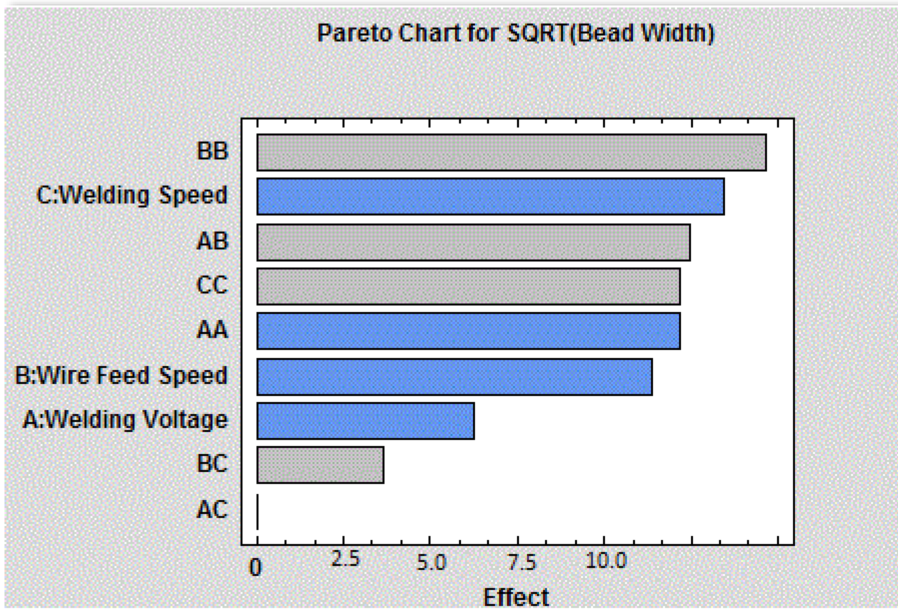


Figure 29: Pareto chart for SQRT of bead width (R3) for GMAW

Based on analysis of variance through ANOVA, the significant controllable factors are identified and then plotted against the standardised effect. Figure 29 shows that Welding speed and wire feed have a significant effect on bead width as compared to other factors [34] , [36] .

5.2.4 ANOVA OF WELD REINFORCEMENT – R4 FOR GMAW

The R-Squared calculation (Table 28) shows that the model as fitted illuminates 44.9561% of the variability in Square root (Depth of Penetration). The adjusted R-squared (the appropriate one) calculation is 0.0 %, The estimated standard error of the residuals to be 0.392887. The mean absolute error of 0.156633 is the average value of the residuals.

Table 28: Variance's analysis for SQRT of weld reinforcement (R4) For GMAW

Factors/ interaction	**Sum of Squares**	**Degree of freedom**	**Mean Square = Sum of Square / DOF**	**F-Ratio = Mean Square / Total Error**	**P-Value = F.DIST(F-ratio,DF1,DF2,FALSE)**
A: Welding Voltage	0.0376313	1	0.0376313	0.24	0.0545
B: Wire Feed Speed	0.0222486	1	0.0222486	0.14	0.04295
C: Welding Speed	0.0523154	1	0.0523154	0.34	0.0513
AA	0.00538944	1	0.00538944	0.03	0.8637
AB	0.0139183	1	0.0139183	0.09	0.7836
AC	0.104516	1	0.104516	0.68	0.04709
BB	0.0264368	1	0.0264368	0.17	0.7068
BC	0.0675445	1	0.0675445	0.44	0.05556
CC	0.0141117	1	0.0141117	0.09	0.05821
Total error	0.46308	3	0.15436		
Total (corr.)	0.841292	12			

Based on analysis of variance through ANOVA, the significant controllable factors are identified and then plotted against the standardised effect. Figure 30 shows that Quadric effects of Welding voltage and welding speed have a significant effect on bead width as compared to other factors [34] , [36] .

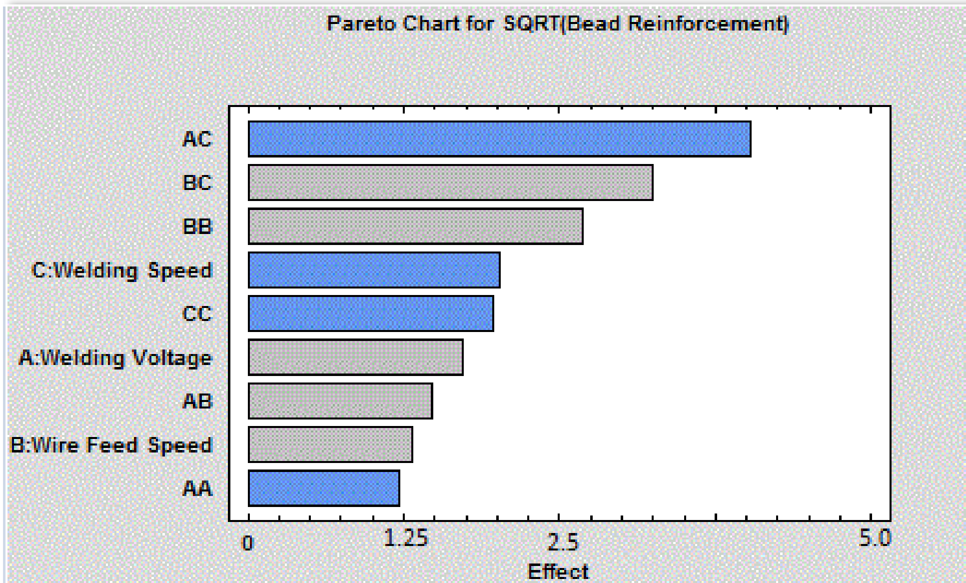


Figure 30: Pareto chart for SQRT of reinforcement height (R4) for GMAW

Since we have executed the design of experiment for GMAW and then segregation of significant and non-significant factors is also done. Now the optimisation will be carried out in chapter 6. The optimisation will be carried out through desirability function to attain the weld joint with Depth of penetration largest-the-best, deposition efficiency larger-the-best et cetera

CHAPTER 6

OPTIMISATION APPROACH OF DESIRABILITY

The chapter discussed the methodologies to find the best weld condition for a similar condition such as outdoor welding by arranging the portable wind protection shed. Most of the researcher used either desirability function analysis or Taguchi quality loss function and, in this thesis, the author used the Taguchi analysis of variances such as the-nominal-the-best, the-smaller-the-better and the-larger-the-best and in the end the calculated results, the desirability function is applied to find the result with higher desirability output to find the optimized results.

1. Taguchi analysis of variance
2. Desirability function analysis

6.1 TAGUCHI ANALYSIS OF VARIANCE

Signal to noise ratio philosophy introduced by Taguchi where significant controllable factors determined by three criteria such as the-nominal-the-best, the-smaller-the-better and the-larger-the-best. Therefore, Table 29 summarised the required output in term of the signal to noise level [34] , [36] ;

Table 29: Summarized the required output in term of the signal to noise level;

Sr.	Factors	S/N ratio Applicable Criteria
1	Depth of Penetration	The-Larger-the-Best (L-Type)

2	Bead Width	The-Nominal-the-Best (N-Type)
3	Deposition Rate	The-Larger-the-Best (L-Type)
4	Hardness of weldment	The-Smaller-the-Better (S-Type)
5	Reinforcement height	The-Smaller-the-Better (S-Type)

6.1.1 THE-LARGER-THE-BEST (L-Type)

For larger the best, we have used the L-Type Equation 26 derived by genichi Taguchi in the quality engineering in production system [36] ;

$$L(y)=\left(A\Delta^2\right)\hat{v}^2 \qquad (26)$$

y = actual value of factor or data point

m = target Value of factor which is infinity

A = Loss caused by exceeding the upper limits

$\hat{v}$ = Variance $= \frac{1}{n}\left(\frac{1}{y_1^2}+\frac{1}{y_2^2}+\frac{1}{y_3^2}+\ldots\ldots\ldots\ldots\ldots+\frac{1}{y_n^2}\right)$

6.1.2. THE-SMALLER-THE-BETTER (S-Type)

For the-Smaller-the-better, we have used the s-type Equation 27 derived by Taguchi in quality engineering in a production system [36] ;

$$L(y)=\hat{v}^2\left(\frac{A}{\Delta^2}\right) \qquad (27)$$

y = actual value of factor or data point

m = target Value of factor

A = Loss caused by exceeding the upper limits

$$\hat{v} = \text{Variance} = \frac{1}{n}\left(y_1^2 + y_2^2 + y_3^2 + \ldots\ldots\ldots\ldots\ldots + y_n^2\right)$$

6.1.3 THE-NOMINAL-THE-BEST (N-Type)

For nominal the best, we have used the N-type Equation 28 derived by genichi Taguchi in the quality engineering in production system. Since in nomial the best case, both tolerances are not equal therefore the following Equation 28 was selected to calculate the signal to noise ratio [36] ;

$$L(y) = \begin{cases} \frac{A_1}{\Delta_1^2}(y\text{-}m)^2 & \text{if} \quad y \leq m \\ \frac{A_2}{\Delta_2^2}(y\text{-}m)^2 & \text{if} \quad y > m \end{cases} \tag{28}$$

Where;

y = actual value of factor or data point

m = target value of the factor

A1 and A2 = tolerance minimum and maximum respectively

6.2 DESIRABILITY FUNCTION ANALYSIS

Desirability is the scale-free value of output data generated through controllable factors. Desirability function methodology is more applicable and flexible as compared to the loss function. The desirability lies between zero and one, and it characterises the closeness of the obtained value with the target value. It means if a response comes beyond the acceptable limits. Then the desirability value will be 0, and it obtains response exactly as required per target value then the desirability will be one. Moreover, if observed response value is not as per target, but it lies between the acceptable tolerances, then the desirability value will be between 0 to 1.

As per definition is given by Harrington [39], "converts every response's value into a scale-free value is known as desirability". The desirability function was also studied and shared by Derringer and Suich's [40] which is used to calculate desirability index for a different condition such as nominal-the best (NTB), larger-the-best (LTB), smaller-the-best (STB) type of measurable responses. In FCAW and GMAW DOE, we have selected the desirability model as required in Equations 29,30 and 31;

$$d_i = \begin{cases} 0, & y_i < L_i \\ \left(\dfrac{y_i - L_i}{T_i - L_i}\right)^{s_i} & L_i \le y_i \le T_i \\ 1, & y_i > \overline{T_i} \end{cases} \tag{29}$$

$$d_i = \begin{cases} 1 & , y_i < T_i \\ \left(\dfrac{H_i - y_i}{H_i - T_i}\right)^{s_i} , & \overline{T_i} \le y_i \le H_i \\ 0 & , y_i > H_i \end{cases} \tag{30}$$

$$di = \begin{cases} 0 & , y_i < Li \\ \left(\dfrac{yi - L_i}{T_i - Li}\right)^{s_i} , & L_i \le y_i \le T_i \\ \left(\dfrac{H_i - y_i}{H_i - T_i}\right)^{s_i} , & Ti \le yi \le Hi \\ 0 & , y_i > H_i \end{cases} \tag{31}$$

In the Equations 29,30,31, L_i will be lower specification limits (<95%), Hi will be upper specification limits (>95%), Ti is target value for the i^{th} response, s_i is the weight given to response how strictly target value required for the process. The individual desirability functions are with exponent “s” determining how important it is to hit the target value . For s =1, the desirability function increases linearly toward T_i , for s < 1 , the function is convex and for s > 1 the function is concave .Equation 29,30 and 31 are individual desirability functions for the whole system collectively desirability is calculated based on Equation 32, which called as composite desirability [40];

$$D_0=(d_1^{W_1}\cdot d_{2-\ldots}^{W_2}\, d_n^{W_n})^{\frac{1}{\Sigma w_i}}. \tag{32}$$

In the composite desirability function, D_0 represent composite desirability, d_1, $d_2 \ldots\ldots d_n$ represents each desirability’s for the ith responses, and Wi is the weight to the target value. For calculating the composite desirability author has given the weight of each response as 0.25 for FCAW/GMAW process. The weight is given based on the criticality and experience, and it equally distributed to all responses.

6.3 OPTIMIZED RESULTS FOR FCAW AND GMAW

FCAW and GMAW’s responses optimised by getting their prediction by taking the mean of lower 95.0% limits and upper 95.0% limit for examples Table 30 and 31 of FCAW and GMAW; the optimised predicted values for hardness, deposition rate, bead width and reinforcement rate are 178.4BHN, 15.05, 10.96mm and 3.5mm respectively. Based on Derringer and Suich’s desirability function as defined above, the desirability calculated for hardness, deposition rate, bead width, and reinforcement height is 73.5 %, 84.23%, 49.34% and 75.81% respectively.

The overall desirability or optimised desirability is equalled 71%, which obtained by considering the desirability of all responses then taking each value to the power equal to its impact, taking the product of both results, and the resultant product raises to a power equal to 1 divided by impact summation. A result is a number between 0 and 1, with more weight given to the response with the higher impact [40].

Table 30: Optimum response values for FCAW

Response	Optimized	Prediction	Lower 95.0% Limit	Upper 95.0% Limit	Desirability (Individual)
Hardness	yes	178.48607	161.74129	195.23086	0.73591323
Deposition Rate	yes	15.054339	14.317798	15.790879	0.84238979
Bead Width	yes	10.960504	9.4417419	12.479266	0.49341736
Reinforcement	yes	3.5161812	2.8917234	4.1406389	0.75809058

Note: The desirability of Responses is enhanced based on the fitted model, and then individual desirability are used to calculate composite desirability as given below;

Composite Desirability $= [d1^{0.25} . d2^{0.25} . d3^{0.25} . d4^{0.25}]^{1/1}$

$= (0.7359)^{0.25} (0.8423)^{0.25}+(0.49341)^{0.25}+(0.7580)^{0.25}$

$= 0.72 = 72\%$

Table 31: Optimum response values for GMAW

Response	Optimised	Prediction	Lower 95.0% Limit	Upper 95.0% Limit	Desirability (Individual)
Depth of Penetration	yes	5.2921	3.47671	7.48744	0.528068
Deposition Efficiency	yes	87.8636	51.8112	133.382	0.853534
Bead Width	yes	7.72064	5.11714	10.8577	0.813758
Bead Reinforcement	yes	2.8614	0.204658	8.58927	0.939741

Note: The desirability of Responses is enhanced based on the fitted model, and then individual desirability are used to calculate composite desirability as given below;

Composite Desirability $= [d1^{0.25} . d2^{0.25} . d3^{0.25} . d4^{0.25}]^{1/1}$

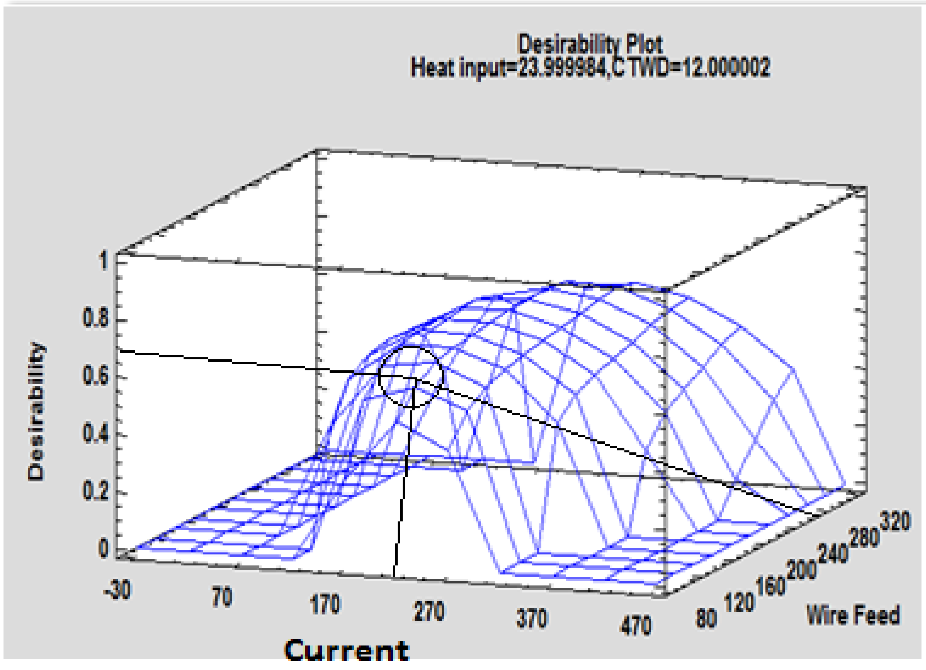
$= (0.5280)^{0.25} . (0.853534)^{0.25} . (0.8137)^{0.25} . (0.9397)^{0.25}$

$= 0.783 = 78\%$

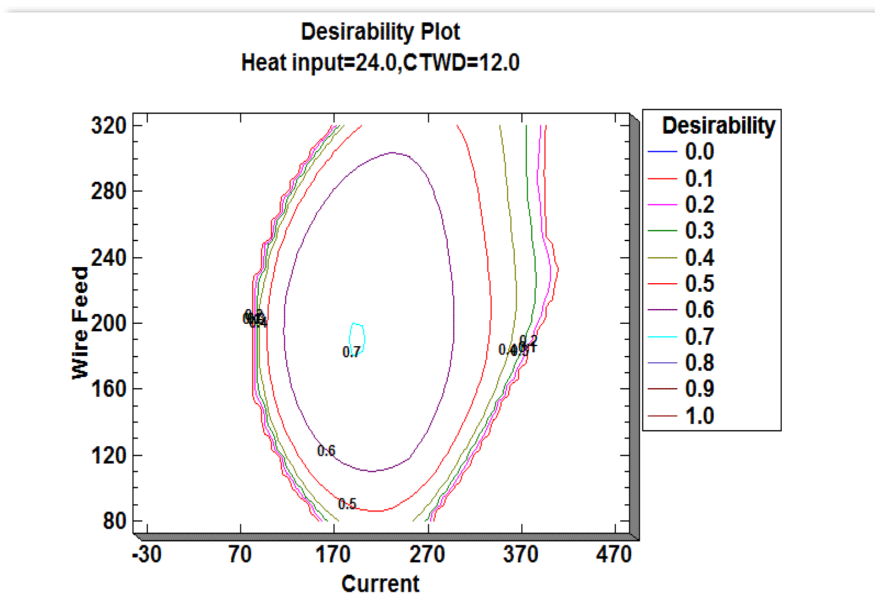
Optimums setting of factors are obtained based on optimised desirability versus optimised responses values and given in Table 32, and the graphical representation mentioned in Figure 31;

Table 32: Factor's settings at optimum for FCAW/GMAW

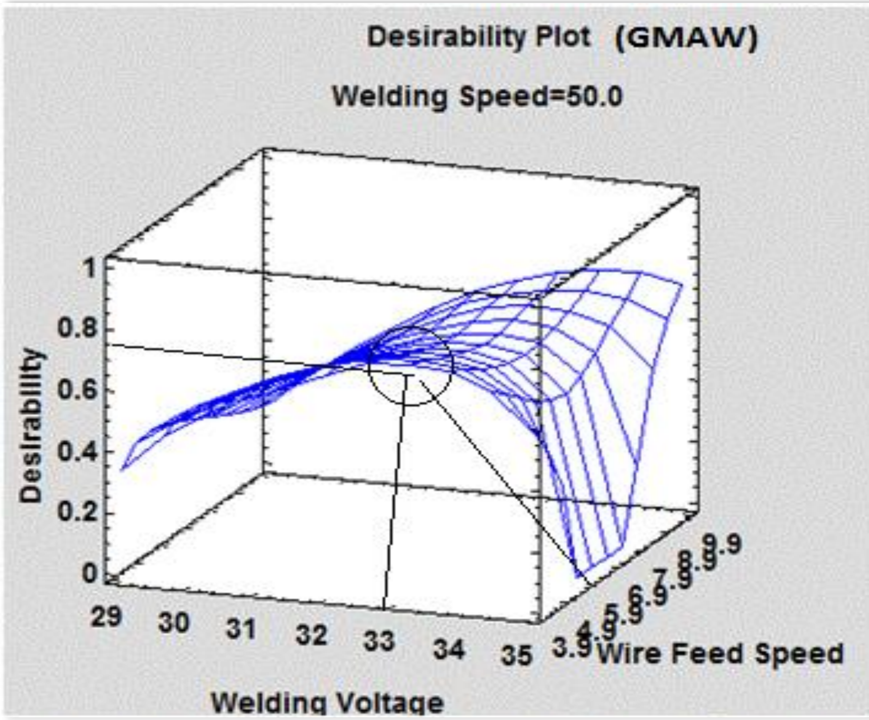
Factors	Optimised Setting for GMAW	Optimised Setting for FCAW
Voltage	33.2 V	-
Wire feed	102 mm/min	266 mm/min
Welding Speed	50 cm / min	-
Heat Input	-	23kj
CTWD	-	12 mm
Current	-	216 A



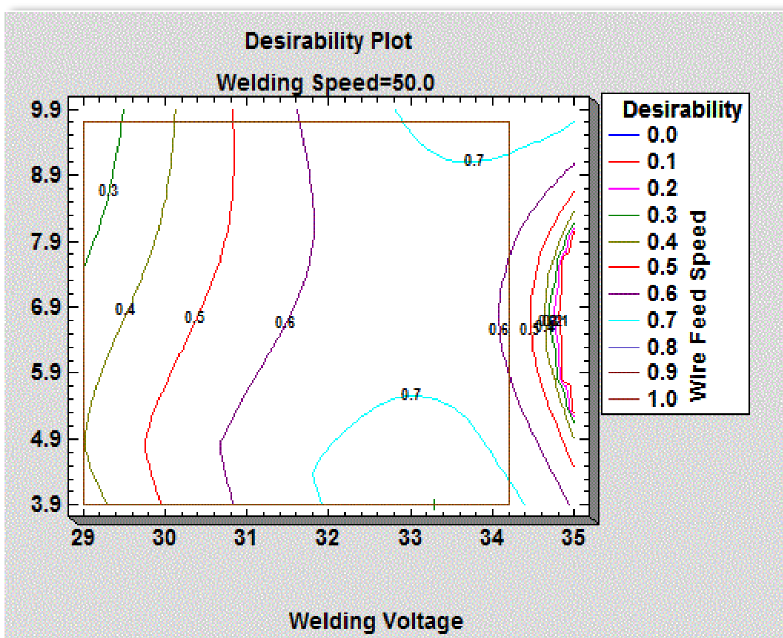
(a) Response surface graph for FCAW showing optimal zone at 72%



(b) FCAW contours for RSM depicting optimal zone at 72%



(c) Response surface graph for GMAW showing optimal zone at 78%



(d) GMAW contours for RSM depicting optimal zone at 78%

Figure 31: Optimum factors setting at the optimum desirability for FCAW/GMAW

The graphical presentation of optimal result shows in Figure 32. Where within the model, controllable welding variables desirability zone is marked in a different colour. Blue colour zone depicted the undesirable zone with a value of 0, and red zone depicts the ideal condition with 100% desirability. Based on welding condition and variables range, optimal desirability zone is 77 % for the given values of welding parameters [34].

CHAPTER 7

EXPERIMENTAL VALIDATION OF PREDICTED RESULTS

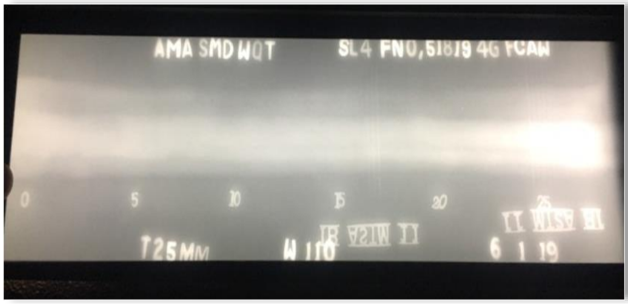
Specific weld coupons are welded to validate the authenticity of obtained optimised values and then the results and data are collected from the test pieces for discussion and to establish the conclusion.

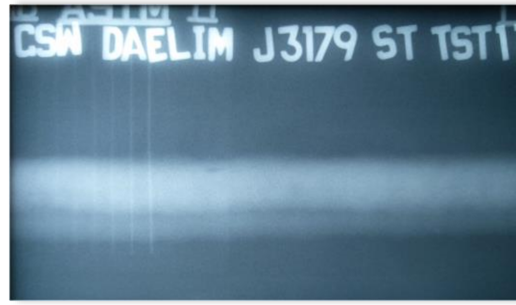
7.1 VALIDATION

After getting the optimal values for factors, the next stage was to validate these values. The run conducted by using these optimal values obtained after these analyses. Welding was performed under the same circumstances using the same material. Results were obtained and found very close to the optimal responses as mentioned in Table 32 and Figure 32;

(a) FCAW validation test coupon

(b) GMAW validation test coupon





(c) Radiography result of FCAW coupon (d) Radiography result of GMAW

(e) Samples for mechanical testing (f) Samples for chemical testing (g) Spectrometer used for testing

Figure 32: Validation testing of FCAW/GMAW (KFUPM Lab.)

Validated samples of FCAW and GMAW tested in KFUPM Testing laboratory where sample was prepared by cutting with Struers made model dichotomy 65 and grinding by 60 grit paper followed by 240 grit, 320 grit, 400 grit and finally by 600 grit and then the cut ground samples polished with micro cloth and Al2O3 power of 0.05 micro-size. We have also taken the hardness value with Buehler USA made model “micromet-3”. To study the material effects, we have prepared the sample etching by etchant natal having ethanol with nitric acid in a ratio of 98:02 respectively. The microscopy and microscopy are done of etched samples by Zeiss model axioplan. Both validated welded test coupons are inspected and tested to collect the welding statistics as explained in chapter 2. With the reference of Equations 04,08,10 and 15 from chapters 2, actual welding responses are calculated and given in Table 33;

Table 33: Validation testing on test coupons

Sr.	Welding Equations	FCAW (ASTM A572)		GMAW (ASTM A36/53)	
		ASTM and	**Actual for weldment**	**ASTM and**	**Actual for weldment**
01	Carbon Equivalent (%)	0.25	KFUPM Lab Results = 0.04 + (1.5/6) + (0.045/5) + (0.0252/15) = 0.04 + 0.25 + 0.001 + 0.002 =0.29 %	0.27	KFUPM Lab Results = 0.0311 + (1.5/6) + (0.02/5) + (0.08/15) = 0.03 + 0.25 + 0.004 + 0.005 =0.28 %
02	Penetration Index (%)	= 25/25 = 1 = 100%	100 % as per Macro Results	= 10/10 = 1 = 100%	100 % as per Macro Results
03	Convexity Index (%)	25-35%	Actual measured =3.0 / 10 = 0.3 = 30%	25-35%	Actual measured = 2.2/6.52 = 0.33 = 33%
04	Heat Input (kJ/mm)	26	Physical measured=216x26x (0.06/14) = 24	25	Physical measured =600x33x (0.06/60) = 23
05	Dye Penetrant test	ASTM /Cp/189	No indication exposed to surface	ASTM /Cp/189	No indication exposed to surface
06	Macrograph	10X / from macrograph of FCAW and GMAW, proper boundary fusion is studied			
07	Micrograph	100X , 200X and 500x			

08	Hardness	Vickers Total samples = 3 FCAW + 3GMAW Hardness Locations = 4 WM + 12 HAZ + 4BM Maximum hardness of WM = 170 HV
09	Dimensional check	Both processes, reinforcement height, penetration depth, bead width measured

In Table 33, carbon equivalent is calculated by entering the alloying chemical composition as measured by a spectrometer, in the CE Equation. Whereas in Spectrometer, the sample material is vaporised with a testing probe by arc spar discharge in atomic vapour emitting radiation. These radiations are passed through the spectrometer dispersing spectral. The range of wavelength emitted by each element is correlated with the stored calibration curve in the device because radiation intensities are propositional to the element's composition in the sample [41].

Hardness measured by Micromet-3 Advance having stringent tolerance for the accuracy of the applied load (0.2%). Travel speed, heat-input and deposition rate is measured with stopwatch manually in the correlation of wire feeder. A calibrated stopwatch was having a resolution of 0.01 second. Weld penetration was measured manually by measuring ruler with measurement accuracy to ± 1 2 of the smallest division on the scale, from the side cross-section of macrograph etched samples and welding reinforcement height measured with welding bridge gauge from the actual sample (with ±1/32" accuracy).

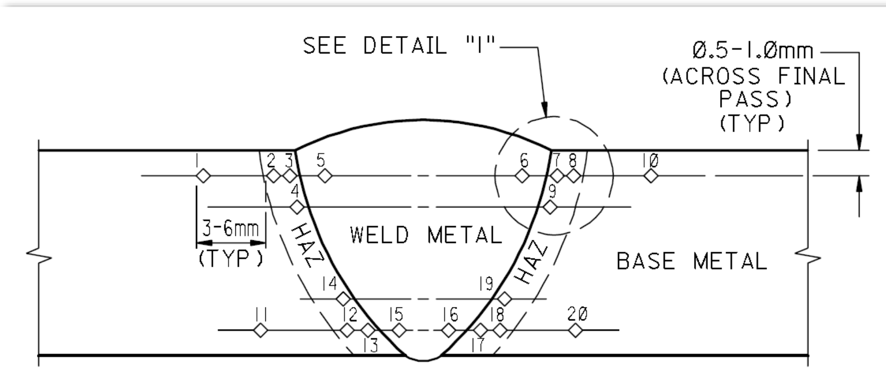
7.1.1 HARDNESS TESTING

One sample of each test coupons tested from KFUPM mechanical lab for Vickers hardness testing, and in addition to KFUPMS testing, the author has taken two of each sample for hardness testing. Location of hardness testing was selected as given in Figure 33 and 34;

Total samples = 3 FCAW + 3 GMAW

Hardness locations = 4 WM + 12 HAZ + 4BM

Maximum hardness of WM = 170 HV



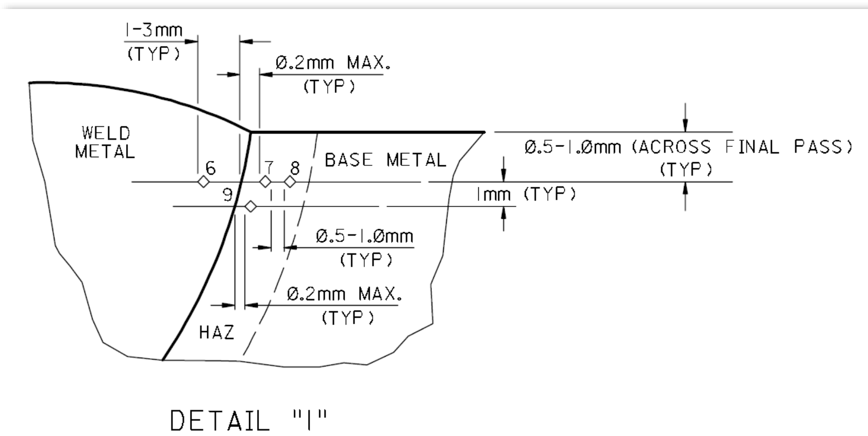
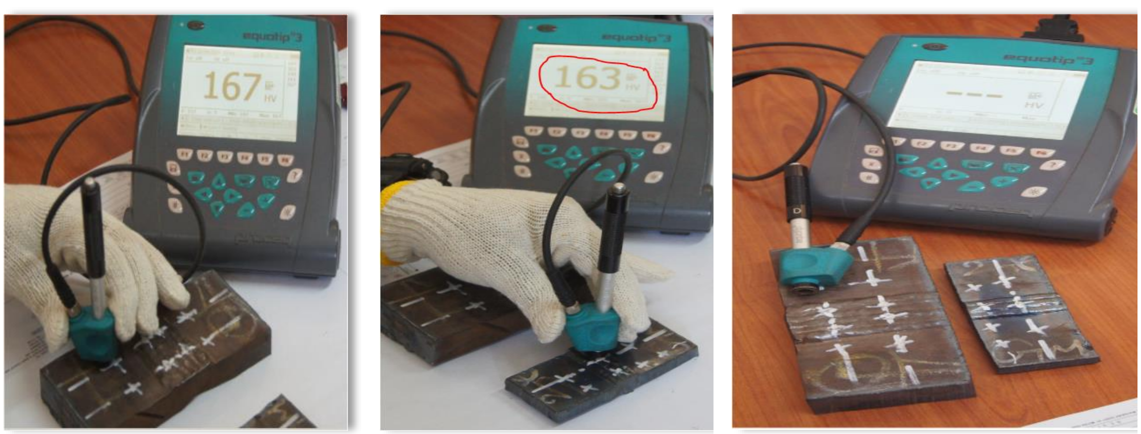
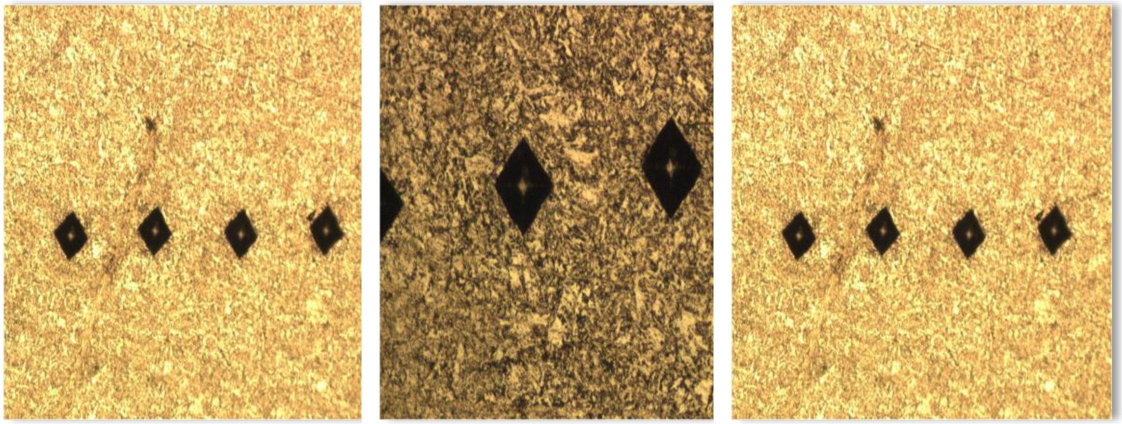


Figure 33: Hardness test's locations selection procedure



(a)



(b)

Figure 34: Hardness testing of FCAW/ GMAW

7.1.2 DYE PENETRANT TESTING

In addition to radiography, the samples were dye penetrant tested in line with ASNT-CP-189 to check the weld defects such as undercut, porosity, crack, underfill et cetera The sample was cleaned through with Meganaflux cleaner followed by application of penetrant. After dowel time of 10 minutes, the developer was applied to check the welding defects through capillary action. Testing of samples shown in Figure 35;

(a)

Figure 35: DPT testing of FCAW/ GMAW test coupons

7.1.3 MACROGRAPHY TESTING

Figure 36 shows the macrography which used for visual and dimensional testing. VT was conducted as per ASNT-CP-189 standard and following are the result where weld's joints found with;

1. Free of spatter
2. 100 % penetration up-to root with completely fused
3. No lack of side wall and root fusion found
4. No porosity and undercut found
5. Reinforcement height measured 3.0 mm
6. Bead width measured 9.9mm

Figure 36 showed the FCAW welding fusion zone, where we can see weld metal have 100% penetration, no lack of fusion, no spatter marks. Reinforcement height is also 3mm. All calculated welding outputs are near optimised values.

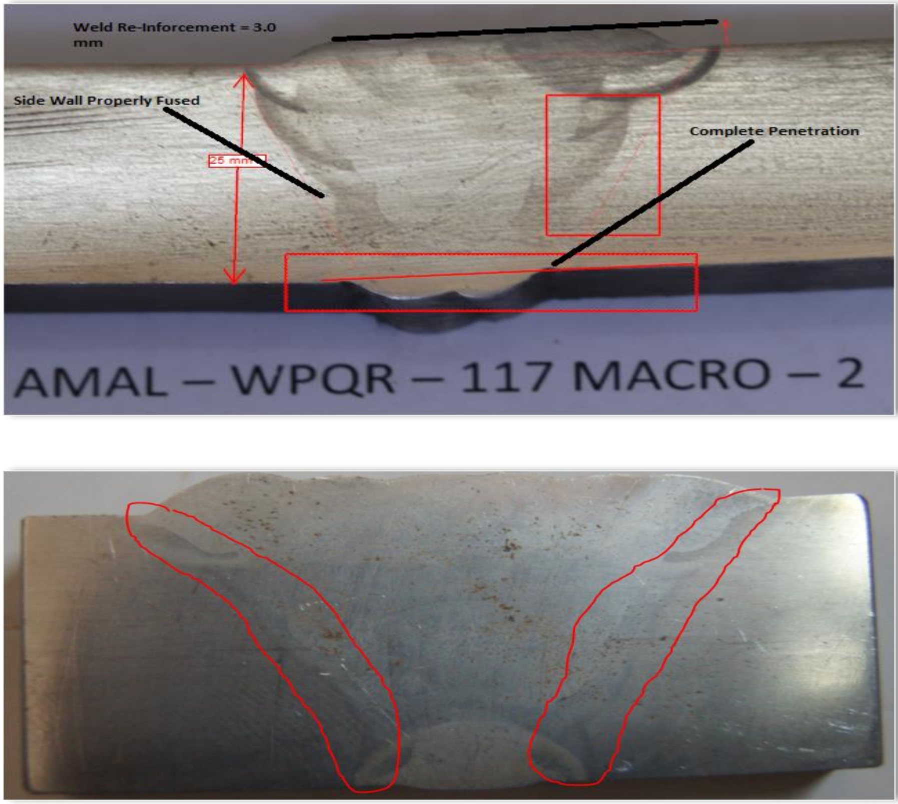


Figure 36: Visual inspection of a micrograph of test samples

7.1.4 MICROGRAPHY OF FCAW AND GMAW SAMPLES

Micrography conducted on validated test samples in KFUPM mechanical laboratory and micrograph is shown in Figure 37, 38, 39, 40, 41 and 42. It is evident from the micro-structural photos that structural shows acicular ferrite and polygonal ferrite with some area little martensite and bainite also detected in weld metal and heat affected zone, whereas for base material which is not being affected with heat is having ferritic and perlitic structures

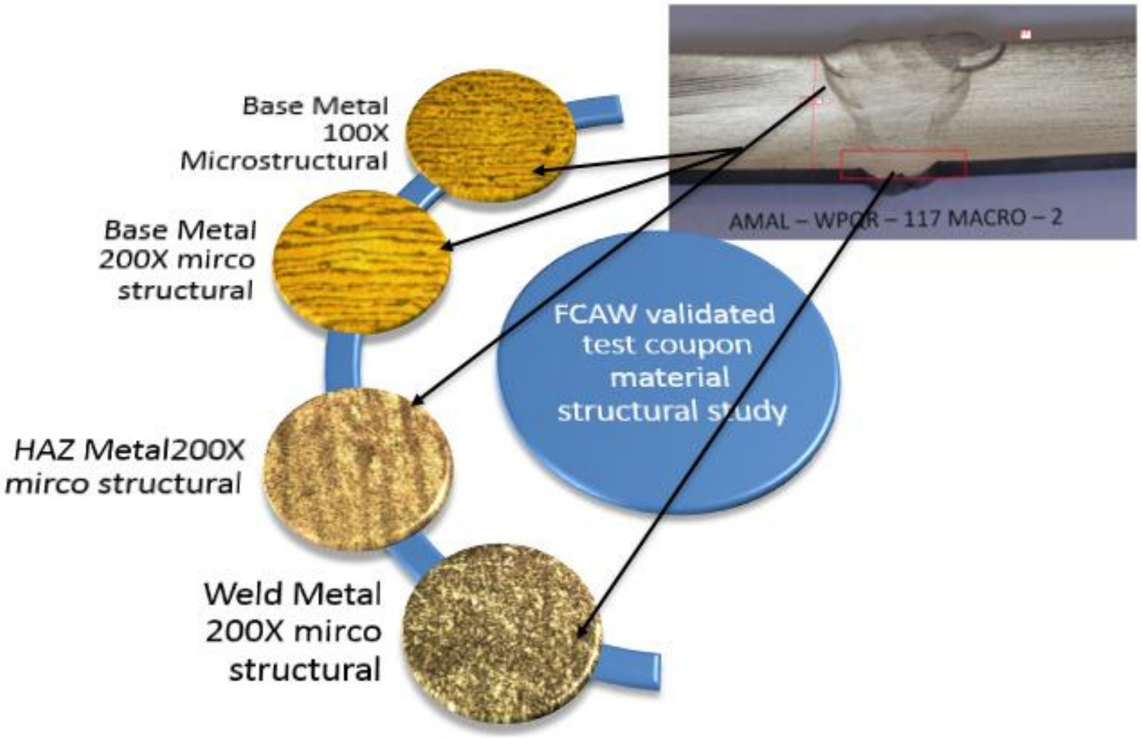


Figure 37: Material structural study FCAW welded joint (Done at KFUPM lab)

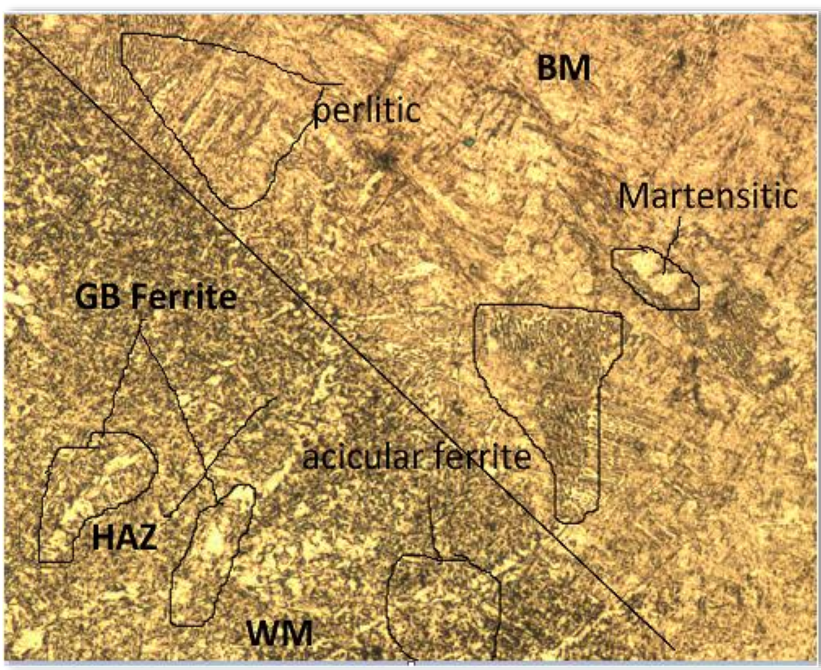


Figure 38: Micrograph showing WM + HAZ (at 200X magnification)

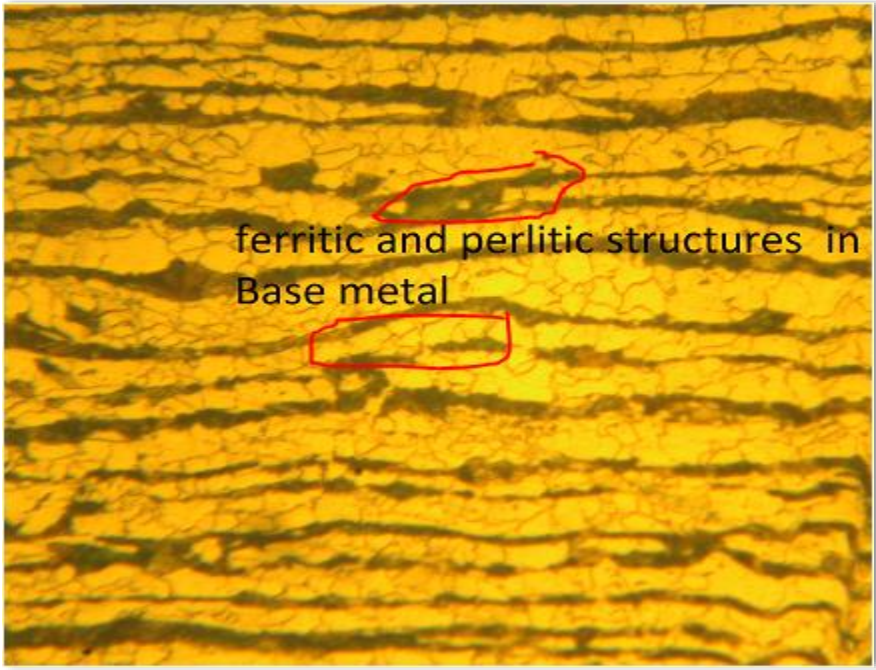


Figure 39: Micrograph showing BM before welding (at 200X magnification)

Welding parameter of the BEST out the BEST weld is substantially relied on heat input, amount of current used and travel speed. The areas with low heat input such as filling (inter bead zone) and capping zone, martensitic and bainite structural specially in grain growth areas along with refine grain but toward root side of weld metal where higher heat input was used to get 100% penetration and to avoid lack of fusion we observed grain growth having ferrite aligned with M-A-C.

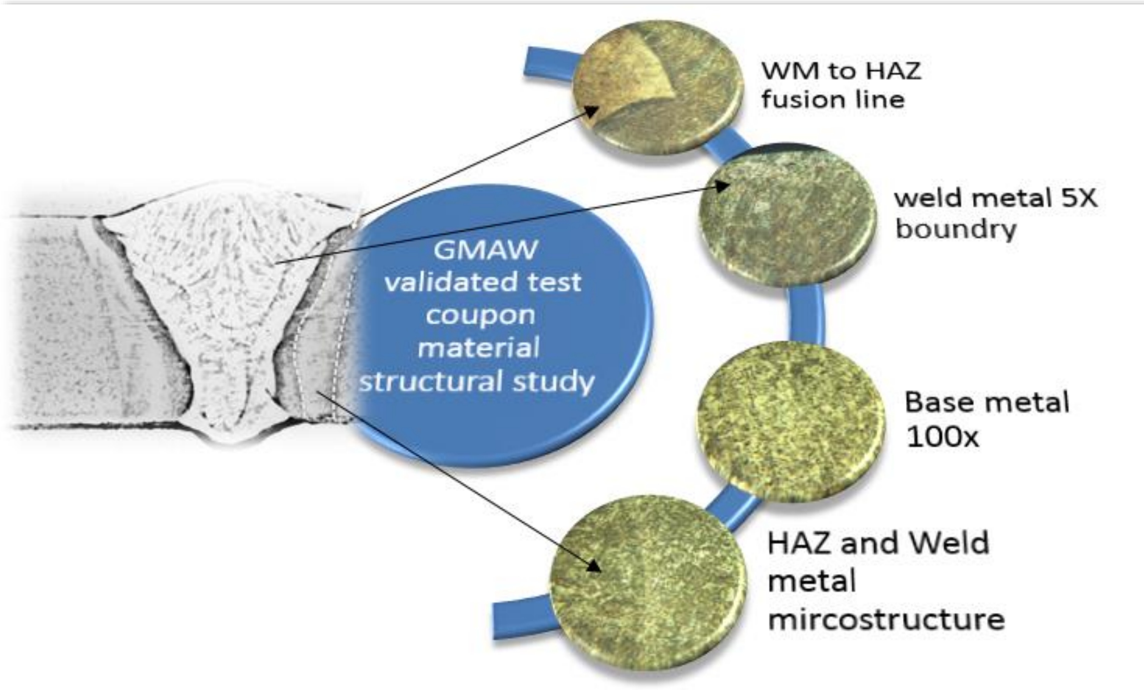


Figure 40: Material structural study GMAW welded joint (KFUPM lab)

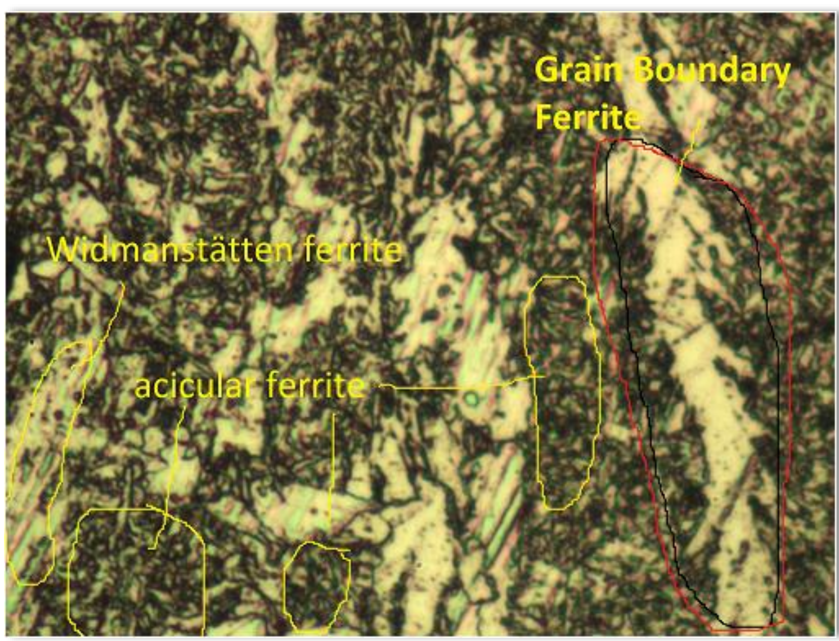


Figure 41: Micrograph showing WM + HAZ (at 100X magnification)

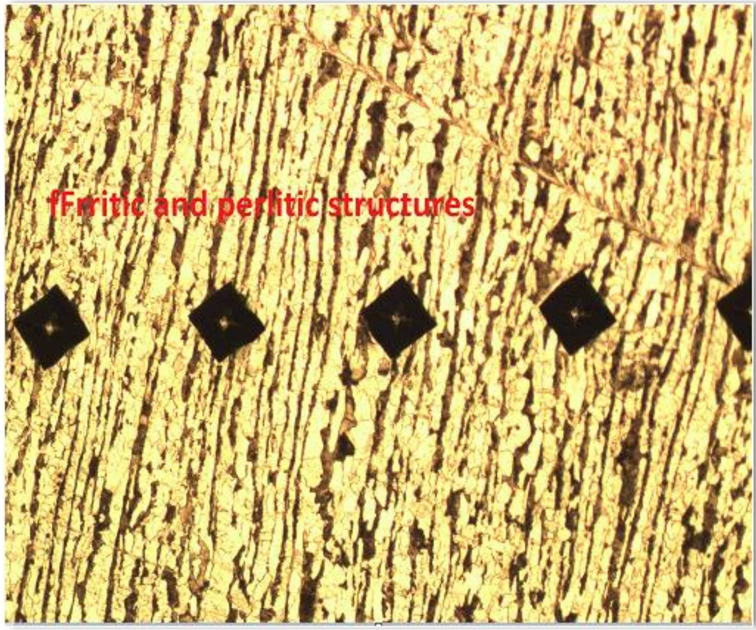


Figure 42: Micrograph showing BM before welding (at 100X magnification)

In the weld metal, we found acicular ferrite with intragranular nucleated widmanstatten ferrite having lath, result in fine grain size as compared to the base metal and this structural result to increase the better toughness having optimised crack propagation capability. Weld metal grain boundaries have a high angle that also increases the crack propagation ability of the weld zone .

7.2 DISCUSSION (OPTIMIZED VALUES VERSUS ACTUAL RESULTS)

Table 34 is the summary of all results comparison between predicted optimised result with the actual results as calculated from validated test coupons.

Table 34: Comparison between optimised and actual results for FCAW / GMAW

Optimised Factors	**Optimised Responses**	**Actual Results (Responses)**

GMAW		
Welding Voltage = 33.2 V	Depth of Penetration = 10 mm	Depth of Penetration = 10 mm
Wire Feed Speed = 102 mm	Deposition Efficiency =87.8 %	Deposition Efficiency = 90 %
Welding Speed = 50 cm/ mm	Bead Width = 7.72 mm	Bead Width = 6.52 mm
	Reinforcement = 2.86 mm	Reinforcement = 2.2 mm
FCAW		
Current = 216.62 A	Hardness = 161 HV	170 HV
Wire Feed = 266.99 mm/min	Deposition rate = 14.35 per min	15 per min
Heat Input = 23.99 KJ	Bead Width = 9.44 mm	10 mm
CTWD = 12 mm	Reinforcement = 2.9 mm	3.0 mm

This study disclosed the application of RSM Box-Behnken and Cube Composite design and desirability analyses for GMAW and FCAW respectively to optimise the welding output. By using these methodologies, optimal values for selected controllable factors and responses found, and then optimal responses values are validated by performing an actual run of the weld and then comparing the actual results with the optimal calculated values. Hence conclusion can be made that for given specific material and similar welding circumstances these analyses can be used for the best(superior) quality weld.

Interaction and effects graph is drawn and reflected in Figure 43 and 44, where Welding bead and deposition rate are directly proportioning to welding current up to saturation limits, and it is evident because of the increase of welding current increases the fluidity of filler wire. Due to increasing the fluidity of molten filler metal, bead width and deposition of filler wire improved toward optimisation value and simultaneous it also increases the weld bead width.

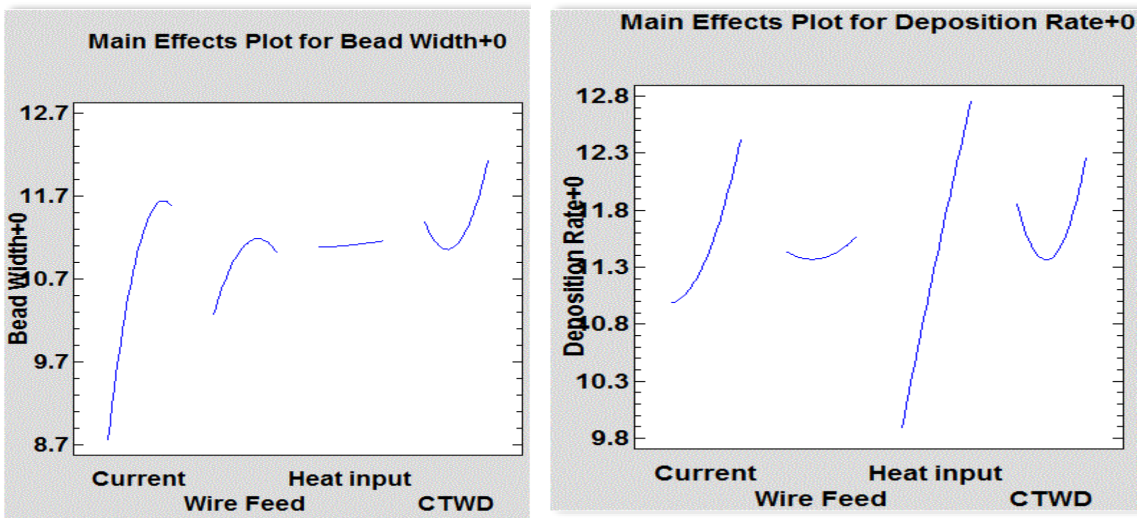


Figure 43: Welding variables effects on bead width and deposition rate

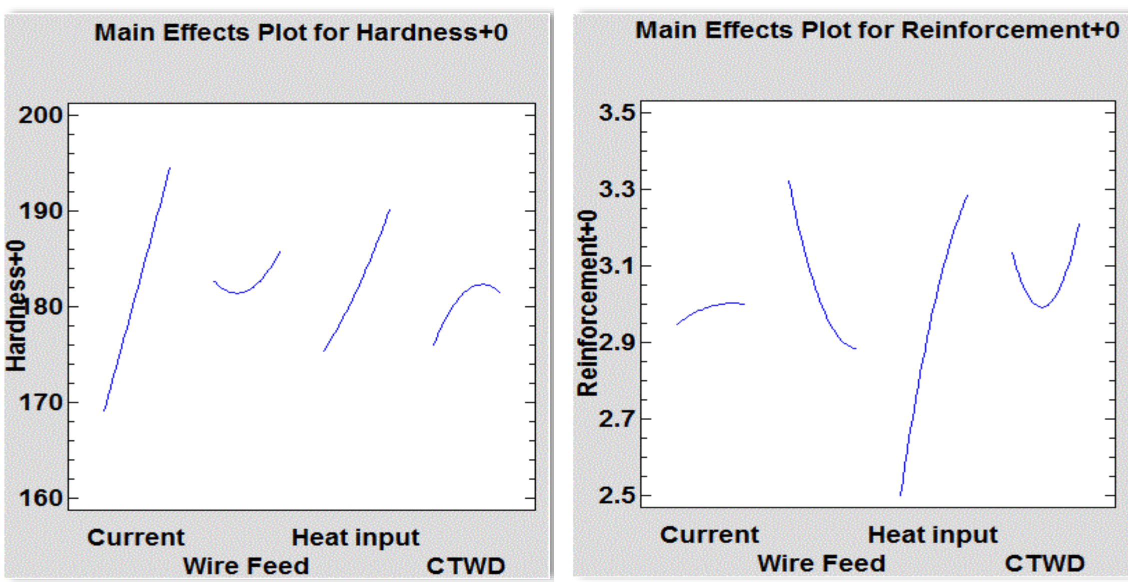


Figure 44: Welding variables effects on hardness and reinforcement

Interaction and effects graph is drawn and reflected in Figure 44. Hardness and reinforcement height are directly proportioning to heat input saturation limits and also it observed that heat input is low at the start of welding process which increases the power density of process .we got complete root penetration, and as welding progress, heat-input increase and power density of welding processes decreased however spatter produced due to decrease of power density . The hardness of weld metal and HAZ and reinforcement of capping increased due to the increase of weld metal amount in one pour.

Welding productivity increased due to the increase of deposition rate by increasing the heat input and current, but other side quality of weld will be compromised because chances to getting welding defects such as spatter, convexity, burn through, undercut, porosity is more by an increase of heat put and current and hardness value. Therefore, optimal values of heat-input and welding characteristic are founded to have best quality weld — outcomes of the thesis mentioned in the next section as a conclusion.

The optimisation outcomes show that penetration will be maximum when current, voltage CTWD are at their maximum possible upper limits. Increase of penetration depth is due to strongly overheating of molten metal droplet leaving the filler wire and the extra heat in droplet contribute the more melting of parent material and in this way increase in current will increase the heat content in droplet and subsequent increase the amount of heat to base metal.

Increase in current is not only strongly overheat the droplet leaving the filler tips but also it shrinks the drop size, increases the momentum of droplet flow and arc force which enables overheated droplet to penetrate deeper up to root edges. Based on this investigation and the above discussion, it can say that developed optimisation can be utilised to attain the quality weld within the specified tolerances of welding variables.

The Thesis is applicable for only ferrous material having carbon equivalency less than 0.3% and thickness less than 25mm for FCAW application and less than 10mm for GMAW application respectively.

CHAPTER 8

CONCLUSIONS AND REMARKS

8.1 CONCLUSIONS

After a thorough study of (GMAW/FCAW) welding processes by deploying the design of experiments and desirability analysis, the conclusions based on experimental validation of the models based predicted results of optimal values are given below;

1. A comprehensive framework of analysis is developed which maximises the quality of the weld through response surface methodology and desirability function which causes the minimum loss to the society. The highest quality weld is based on narrow down boundary limits of the ordinarily acceptable range of weld features from the international standard. The modelling strategy deployed in this framework is driven by the field data of respective welding obtained in accordance with a suitable Design of Experiments scheme. The optimised values of the resulting enhanced quality welds are in accordance with the following goals: hardness value as nominal the best, tensile strength value with larger the best, a bead width value as nominal the best.
2. The optimal results predicted by the models are validated experimentally for the carbon steel of the ASME group “P1” with material thickness less than 25mm. The framework developed can be applied to other thicknesses and weld materials for their respective new welding process data input.

3. The welding quality characteristics, of the weld, made at optimised predicted conditions, such as deposition rate, penetration index, reinforcement height of the welding and weld geometry were in good agreement with the predictions through the desirability functions and relevant indices computed.
4. The output weld is free from blow holes, spatters, undercut, uneven deposition, excessive penetration and reinforcement, crack and lack of sidewall fusion when welded on optimised condition Moreover, it is also noticed through micrographic analysis that refined and smooth material structural observed in weld and heat effective zone ensure the high weld reliability (quality during the service life).
5. For FCAW/GMAW, heat input and interaction of current and travel speed are the most critical factors and combination for getting welds free from spatters, undercut, lack of sidewall fusion, lack of root penetration and fusion. For reinforcement height electrode manipulation and welding, speed is major contributing factors followed by voltage.

8.2 REMARKS

Some other remarks relevant to this study are ;

1. Factorial method for the design of experiments is most useful because it enables us to find which factors are essential and which interaction has the most influential effects on desirability.
2. The response surface methodology is most appropriate as compared to the Taguchi method for finding the factor's interaction significance and square terms of parameters.

3. The thesis's framework of the analyses can be applied for any such welding case and can be combined in a single software package to find optimal weld conditions leading to enhanced weld quality which is also indirectly indicating the least number of discontinuities per weld as verified by high spatter index.

APPENDIX – I

FCAW WPS

AHMED MANSOOR AL-A'ali Co.Bsc (C)

WELDING PROCEDURE SPECIFICATION (WPS)

WPS No.:	FCAW-03A Rev. No.: 0	Date:	13.11.2018
Supporting PQR No(s).:	AMA-SMD/Gr2-Gr2/FCAW/03	Code:	AWS D1.1
Welding Process(es):	FCAW	Type(s):	Semi-Automatic

BASE METAL(S) :

P.No. - Group No. 1, 2 To P.No. - Group No. 1, 2

Or Material Spec. ______ To ______

Base Metal Thickness Range (mm):

Groove: 3mm to Unlimited Fillet: All

Max.Pass Thk.≤13mm : (Yes.) ☑ (No.) ☐

Others:

JOINTS :

Joint Design:	As per applicable drwg.
Root Spacing:	As per applicable drwg.
Backing:	Yes and/or No
Backing material :	Weld, Base metal
☑Metal ☐Nonfusing Metal ☐Nonmetallic ☐ Other	
Retainer:	No

FILLER METALS :

Welding Process:	FCAW
Specification No (SFA):	5.36
AWS No. Classification:	E71T-1C
Filler Metal F.No.:	6
Weld Metal A.No.:	1
Size of Filler Metals(mm):	Ø0.8, 1.2, & 1.4mm
Filler Metal Product Form:	Flux Cored
Supplemental Filler Metal:	NA
Weld Metal Depo. Thk. (mm):	
Groove:	3mm to Unlimited
Fillet:	All
Alloy Elements	NA
Flux Type:	NA
Flux Trade Name:	NA
Consumable Insert:	NA
Others:	Nil

POSITION :

Positions of Groove:	OVERHEAD
Welding Progression:	NA
Positions of Fillet:	OVERHEAD
Others:	Nil

PREHEAT :

Preheat Temp. (min.):	10°C (Ambient) *
Interpass Temp.(max.):	250°C
Preheat Maintenance:	NA
Others:	Nil

PWHT :

Temperature (Range):	NA
Time Range:	NA
Others:	Nil

GAS :	Gas	% Mixture	Flow Rate
Shielding	Co2	100%	12-20
Backing	NA	NA	NA
Trailing	NA	NA	NA
Others:			

TECHNIQUE :

String / Weave Bead:	String and Weave
Orifice/ Nozzle/Gas cup size .:	10 to 22mm
Method cleaning:	Wire-Brush, Grinding
Method of back gouging:	Arc Gouging / Grinding (If Required)
Oscillation:	NA
Contact tube to work dist.:	15-25mm
Single or Multiple pass/side:	Single or Multiple
Single/ Multiple Electrodes:	Single
Use of Thermal Processes	NA
Peening:	Not Allowed
Others:	Nil

ELECTRICAL CHARACTERISTICS :

Welding Process:	FCAW
Pulsing Current (Yes/No):	NA
Heat Input (Max.)	NA
Tungsten Electrode Dia.:	NA
Tungsten Electrode Type:	NA
Mode of Metal Transfer for	SPRAY ARC, GLOBULAR ARC
Others:	Nil

Weld Pass(es)	Process	Filler Metal		Current (A)			Energy or Power Range	Volt Range(V)	Travel Speed (mm/min.)	Wire Feed Speed
		Class	Dia.(mm)	Type	Polarity	Amp.Range				
Any	FCAW	E71T-1C	0.8	DC	EP	90-140	NA	14-24	170 to 240	NA
	FCAW	E71T-1C	1.2	DC	EP	110-180	NA	18-28	170 to 240	NA
	FCAW	E71T-1C	1.4	DC	EP	150-260	NA	22-32	170 to 240	NA

REMARKS (IF ANY):

* Note 1. Preheat Temperature should be 65°C when thickness is more than 38 thru 65 mm.

Note 2. Preheat Temperature should be 110°C when thickness is more than 65 mm.

Prepared By: DHAVAL JOSHI

Sign / Date:

Approved By: SHEIK MOOSA

Sign / Date:

GMAW WPS

Saudi Aramco | Hanwha E&C | JAZAN REFINERY & TERMINAL PROJECT
PKG#14 MARINE TERMINAL FACILITIES

AWS D1.1/D1.1M 2010

ANNEX N

WELDING PROCEDURE SPECIFICATION (WPS) Yes ■ ✓
PREQUALIFIED YES **QUALIFIED BY TESTING**
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☐

Identification # **JRTP014-GE008-NSH-0019**
Revision **B** Date **24-Oct-15** BY **RIJO THOMAS**
Authorized by **MAHESH MADHU** Date **24-Oct-15**
Type-Manual ☐ Semi-Automatic ■ ✓
Machine ☐ Automatic ☐

Company Name: **Nasser S Al-Hajri Corporation**
Welding Process(es): **GMAW** ✓
Supporting PQR No.(s): **Prequalified** ✓

JOINT DESIGN USED
Type: **FILLET** ✓
Single ■ ✓ Double Weld ☐
Backing: Yes ✓ No
Backing Material: -
Root Opening: -
Root Face Dimension: -
Groove Angle: - Radius (J-U): -
Back Gouging: Yes No ■ ✓ Method: -

POSITION
Position of Groove: - Fillet: **ALL**
Vertical Progression: Up ■ ✓ Down ☐

ELECTRICAL CHARACTERISTICS
Transfer Mode (GMAW): Short-Circuiting ☐ Globular ■ ✓ Spray ☐
Current: AC ☐ DCEP ■ ✓ DCEN ☐ Pulsed ☐
Other
Tungsten Electrode (GTAW)
Size: **NA** ✓
Type: **NA** ✓

BASE METALS
Material Spec.: **A 36,A 53 or Equivalent of ASTM Materials** ✓
Type or Grade: **Gr.B or Equivalent of ASTM Materials.** ✓
Thickness: Groove - Fillet **Unlimited** ✓
Diameter (Pipe): -
Fillet Weld Size: **As per AWS D1.1 Table 5.8 (3 mm min).** ✓
Minimum Fillet weld size shall be increase based on plate thickness per AWS D1.1 Table 5.8 or as detailed in drg.

FILLER METALS
AWS Specification: **AWS 5.18**
AWS Classification: **ER 70S-6**

TECHNIQUE
Stringer or Weave Bead: **Stringer &Weave Bead**
Multi-pass or Single pass (per side): **Single pass & Multiple pass**
Number of Electrodes: **1**
Electrode Spacing: Longitudinal **NA**; Lateral **NA**; Angle **NA**
Contact Tube to Work Distance: **15 - 25 mm** ✓
Peening: **NONE**
Interpass Cleaning: **Brushing** ✓

SHIELDING
Flux: **NA** Gas: **CO2**
Composition: **100%**
Electrode-Flux (Class): - Flow Rate: **15 - 30CFH** ✓
- Gas Cup Size: **NA**

PREHEAT
Preheat Temp., Min

BASE METAL THICKNESS	TEMP.
3-20 mm	10°C ✓
20-38 mm	65°C ✓
38-65 mm	110°C ✓

Inter pass Temp, Min- same as pre heat

POSTWELD HEAT TREATMENT
Temp.: **N/A**
Time: **N/A**

WELDING PROCEDURE

Pass or Weld Layer(s)	Process	Filler Metals		Current		Volts	Wire Speed(m m/min)	Travel Speed(mm /min)	Joint Details
		Class	Dia. (mm)	Type & Polarity	Amps				
Root	GMAW	ER 70S-6	1.2MM	DCEP	130-150	20 - 23	130-145	130-150	CHECK PAGE NO:05
Fill & Capping	GMAW	ER 70S-6	1.2MM	DCEP	130-150	20 - 23	130-145	130-150	

We undersigned certify that the information stated on this WPS conforms to the requirements of AWS D1.1/D1.1M - Structural Welding Code - Steel

Approved by Sub-Contractor Quality Manager
Name: MAHESH MADHU
Signature:
Date: 24-10-2015

Sheet : 03 of 05

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VITAE

Name	: KASHIF NAZIR
Nationality	: PAKISTANI
Date of Birth	: JULY 09, 1983
Email	: kashif9003@gmail.com
Address	: Manama Bahrain
Academic Background	: BE Engineering