

**Optimization of Welding Parameters for Ultimate Tensile Strength of SS
202 Alloy using TIG Welding**

*A Project report submitted in partial fulfillment of the requirement for
the award of the degree of*

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IN

MECHANICAL ENGINEERING

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Andhra University, Approved by AICTE, Accredited by NBA & NAAC with 'A' grade)**

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CERTIFICATE

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ABSTRACT

In many Production contexts, it is still necessary to rely on engineering judgment to optimize a multi-response problem, therefore uncertainty seems to prevail during the decision making process. Therefore development of efficient multi-response phenomena is required. The present project deals with the optimization of welding parameters for ultimate tensile strength of SS 202 alloy using TIG welding with the help of Design of Experiments (DOE). The experiment has been carried out by using TIG welding and ultimate tensile testing machine and stainless steel SS 202 as work piece. The approach is based on full factorial method using MINITAB package. The inputs are current, gas flow rate and filler rod diameter while the response is tensile strength.

Keywords

Optimization, TIG welding, tensile strength, fractional factorial method

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CHAPTER 1

INTRODUCTION

1.1. WELDING

The process of welding is an integral part of manufacturing of nuclear components and has a direct influence on the integrity of the components and their thermal and mechanical behavior during service. Welding is a crucial manufacturing process and widely used in industries to assemble various products including ships, automobiles, trains and bridges. Welding distortion often results in problems such as dimensional inaccuracies during the assembly and increased fabrication costs. Therefore, prediction and reduction of welding distortion are critical to improve the quality of welded structures. Welding distortions during the assembly process are affected by not only local shrinkage due to rapid heating and cooling, but also due to root gap and misalignment between parts to be welded. There are three fundamental dimensional changes resulting during welding - Transverse shrinkage that occurs perpendicular to the weld line, Longitudinal shrinkage that occurs parallel to the weld line and, Angular change that consists of rotation around the weld line. To mitigate or minimize distortion, it is important to know their quantitative values in advance. The best approach is to simulate the welding process using modeling tools to predict the thermal cycles, residual stresses and distortion. Recent advancement in the computational methods makes it possible to simulate complex fusion welding processes in shorter duration with a good accuracy. The numerical simulation helps to establish an acceptable weld procedure by replacing the normal experimental trial and error approach.

1.1.1. Types of welding

Some of the best known welding methods include:

- **Oxy-fuel welding**– Also known as “oxyacetylene welding” or “oxy welding”, it uses fuel gases and oxygen to weld and cut metals.
- **Shielded metal arc welding (SMAW)** –Also known as “stick welding” or “electric welding”, it uses an electrode that has flux around it to protect the weld puddle. The electrode holder holds the electrode as it slowly melts away. Slag protects the weld puddle from atmospheric contamination.

- **Gas tungsten arc welding (GTAW)** – Also known as TIG (Tungsten Inert Gas), it uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by an inert shielding gas such as Argon or Helium.
- **Gas metal arc welding (GMAW)** – Commonly termed as MIG (Metal Inert Gas), it uses a wire feeding gun that feeds wire at an adjustable speed and flows an Argon-based shielding gas or a mix of Argon and carbon dioxide (CO₂) over the weld puddle to protect it from atmospheric contamination.
- **Flux-cored arc welding (FCAW)** – It is almost identical to MIG welding except it uses a special tubular wire filled with flux; it can be used with or without shielding gas, depending on the filler.
- **Submerged arc welding (SAW)** –It uses an automatically fed consumable electrode and a blanket of granular fusible flux. The molten weld and the arc zone are protected from atmospheric contamination by being “submerged” under the flux blanket.
- **Electroslag welding (ESW)** –This is a highly productive, single pass welding process for thicker materials between 1 inch (25 mm) and 12 inches (300 mm) in a vertical or close to vertical position.
- **Electric resistance welding (ERW)** –It is a welding process that produces coalescence of laying surfaces where heat to form the weld is generated by the electrical resistance of the material. In general, it is an efficient method, but is limited to relatively thin material.

Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. While often an industrial process, welding may be performed in many different environments, including in open air, under water, and in outer space.

1.2 GAS TUNGSTEN ARC WELDING (GTAW)

Gas tungsten arc welding (GTAW) is an extremely important arc welding process that uses a non-consumable tungsten electrode and an inert gas for arc shielding. It is commonly used for welding hard-to-weld metals, such as aluminium, stainless steel, magnesium and titanium. The gas tungsten arc welding process (Fig. 1.1), uses an electric arc, established by a non-consumable tungsten electrode and the base metal, to join the metal

being welded. A separate welding filler rod is fed into the molten base metal, if needed. The torch holding the tungsten electrode is connected to a shielding gas cylinder and to one of the terminals of the power source. The tungsten electrode is usually in contact with a water-cooled copper tube, called the contact tube, which is connected to the terminal as well. This allows the welding current to enter the electrode and also the cooling of the electrode to prevent overheating. The work piece is connected to the other terminal of the power source through a different cable. The shielding gas goes through the torch body and is directed by a nozzle toward the weld pool to protect it from the surrounding atmosphere. The gaseous protection in GTAW is much better than SMAW, because an inert gas, such as Argon or Helium, is usually used as the shielding gas and it is directed towards the weld pool. In the GTAW process, three different polarities can be achieved. The current being used may be AC or DC; where DC is subdivided according to the electrode polarity (negative or positive).

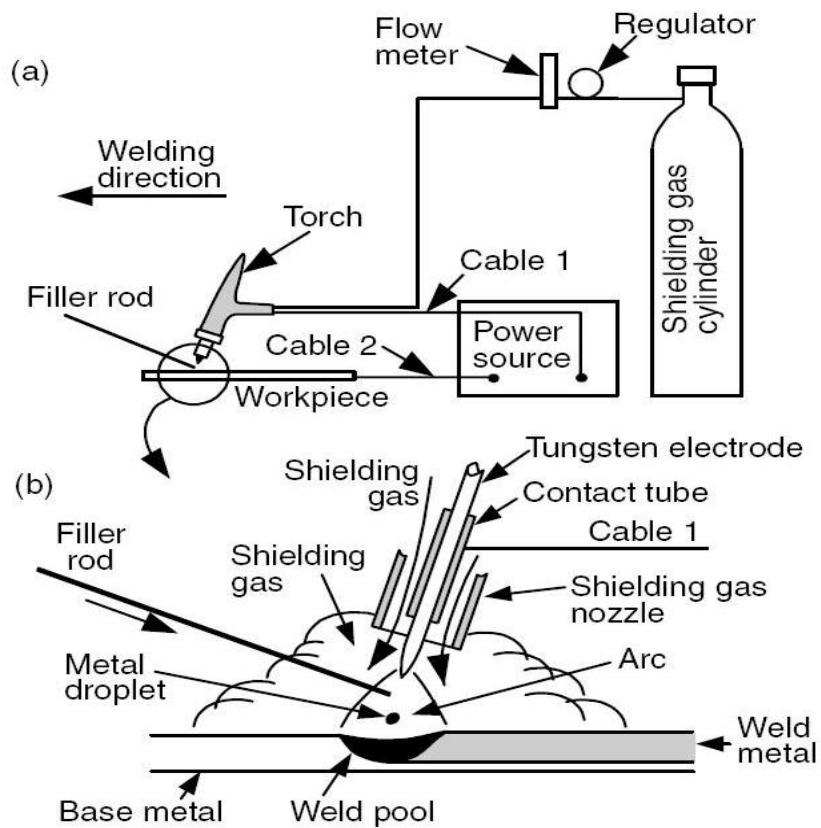


Fig. 1.1 Gas Tungsten Arc Welding Process a) Overall Process and b) Welding area
In a more detailed description the polarities are:

A. Direct current electrode negative (DCEN) - This, also called straight polarity, is the most common polarity in GTAW. With DCEN, the amount of power located in the work piece is more than the one at the end of the electrode. In this way, a relatively narrow and deep weld pool is produced as shown in Fig.1.2 (a).

B. Direct current electrode positive (DCEP) - This is also called reverse polarity. Consequently, with DCEP, more power will be located at the electrode, which is why water-cooled electrodes must be used, and less penetration of the weld metal will be achieved (Fig. 1.2 (b)). Also, positive ions of the shielding gas will bombard the base metal, knocking off oxide films and producing a clean weld surface.

C. Alternative current (AC) - As illustrated in Fig.1.3 (c), a reasonably good penetration and oxide cleaning action can be obtained.

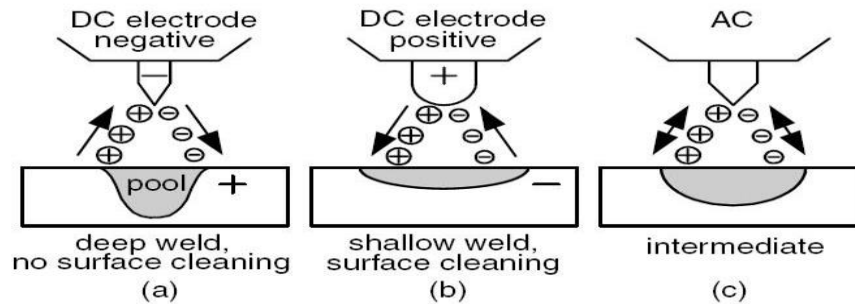


Fig. 1.2 Three different polarities in GTAW (a) DCEN (b) DCEP (c) AC

As shielding gases, both Argon and Helium can be used in the GTAW process. The ionization potentials for Argon and Helium are 15.7 and 24.5 eV respectively. Since it is easier to ionize Argon than Helium, arc initiation is easier and the voltage drop across the arc is lower with Argon. Also, Argon is heavier than Helium, offering a more effective shielding in the weld pool. These advantages, plus the lower cost of Argon, make it more attractive for GTAW than Helium.

1.3. TENSILE STRENGTH

Ultimate tensile strength (UTS), often shortened to tensile strength (TS), is the capacity of a material or a structure to withstand loads tending to elongate, as opposed to compressive strength, which withstands loads tending to reduce size. In other words, tensile strength resists tension (being pulled apart), whereas compressive strength resists compression (being pushed together). Ultimate tensile strength is measured by the

maximum stress that a material can withstand while being stretched or pulled before breaking. In the study of strength of materials, tensile strength, compressive strength, and shear strength can be analyzed independently.

Some materials break very sharply, without plastic deformation, in what is called a brittle failure. Others, which are more ductile, including most metals, experience some plastic deformation and possibly necking before fracture. Tensile strengths are rarely used in the design of ductile members, but they are important in brittle members. They are tabulated for common materials such as alloys, composite materials, ceramics, plastics, and wood.

Tensile strength can be defined for liquids as well as solids under certain conditions. For example, when a tree draws water from its roots to its upper leaves by transpiration, the column of water is pulled upwards from the top by the cohesion of the water in the xylem, and this force is transmitted down the column by its tensile strength. Air pressure, osmotic pressure, and capillary tension also plays a small part in a tree's ability to draw up water, but this alone would only be sufficient to push the column of water to a height of less than ten meters, and trees can grow much higher than that (over 100 m).



Fig. 1.3 Tensile testing

Tensile strength is defined as a stress, which is measured as force per unit area. For some non-homogeneous materials (or for assembled components) it can be reported just as a force or as a force per unit width. In the International System of Units (SI), the unit is

the Pascal (Pa) (or a multiple thereof, often Mega-Pascal (MPa), using the SI prefix mega); or, equivalent to Pascal, Newton per square metre (N/m²).

A United States customary unit is pounds per square inch (lb/in² or psi), or kilo-pounds per square inch (kpsi, or sometimes ksi), which is equal to 1000 psi; kilo-pounds per square inch are commonly used in one country (US), when measuring tensile strengths.

There are three typical definitions of tensile strength:

- **Yield strength** – Yield strength is the stress that a material can withstand without permanent deformation. This is not a sharply defined point. Yield strength is the stress which will cause a permanent deformation of 0.2% of the original dimension.
- **Ultimate strength** - The maximum stress a material can withstand.
- **Breaking strength** - The stress coordinate on the stress-strain curve at the point of rupture.

1.3.1. Ductile Materials

Many materials can display linear elastic behavior, defined by a linear stress–strain relationship, as shown in Fig 1.3., up to point 3. The elastic behavior of materials often extends into a non-linear region, represented in Fig 1.3., by point 2 (the "yield point"), up to which deformations are completely recoverable upon removal of the load; that is, a specimen loaded elastically in tension will elongate, but will return to its original shape and size when unloaded. Beyond this elastic region, for ductile materials, such as steel, deformations are plastic. A plastically deformed specimen does not completely return to its original size and shape when unloaded. For many applications, plastic deformation is unacceptable, and is used as the design limitation.

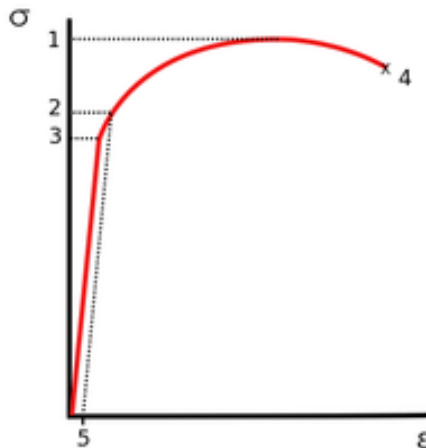


Fig. 1.4 "Engineering" stress–strain (σ – ϵ) curve typical of aluminum

1. Ultimate strength
2. Yield strength
3. Proportional limit stress
4. Fracture
5. Offset strain (typically 0.2%)

After the yield point, ductile metals undergo a period of strain hardening, in which the stress increases again with increasing strain, and they begin to neck, as the cross-sectional area of the specimen decreases due to plastic flow. In a sufficiently ductile material, when necking becomes substantial, it causes a reversal of the engineering stress–strain curve (curve A, Fig 1.4); this is because the engineering stress is calculated assuming the original cross-sectional area before necking. The reversal point is the maximum stress on the engineering stress–strain curve, and the engineering stress coordinate of this point is the ultimate tensile strength, given by point 1.

1.3.2. Tensile Testing

Tensile testing, also known as tension testing, is a fundamental materials science and engineering test in which a sample is subjected to a controlled tension until failure. Properties that are directly measured via a tensile test are ultimate tensile strength, breaking strength, maximum elongation and reduction in area. From these measurements the following properties can also be determined: Young's modulus, Poisson's ratio, yield strength, and strain-hardening characteristics. Uniaxial tensile testing is the most

commonly used for obtaining the mechanical characteristics of isotropic materials. Some materials use biaxial tensile testing.

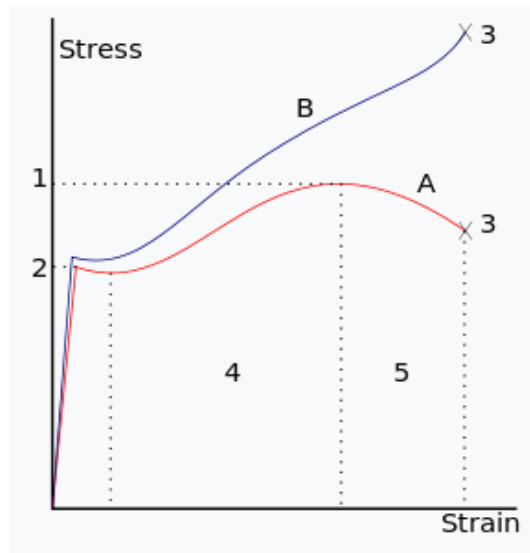


Fig. 1.5 "Engineering" (red) and "true" (blue) stress–strain curve typical of structural steel.

1: Ultimate strength

2: Yield strength (yield point)

3: Rupture

4: Strain hardening region

5: Necking region

A: Apparent stress (F/A_0)

B: Actual stress (F/A)

1.4. MINITAB SOFTWARE

Minitab is a statistics package developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in 1972. It began as a light version of OMNITAB, a statistical analysis program by NIST; the documentation for OMNITAB was last published 1986, and there has been no significant development since then. Minitab is distributed by Minitab, Inc., a privately owned company headquartered in State College, Pennsylvania. Minitab introduces the most commonly used features such as you use functions, create graphs, and generate statistics. We use a sampling of Minitab's

features to see the range of features and statistics that Minitab provides. Most statistical analyses require a series of steps, often directed by background knowledge or by the subject area we are investigating.

The following illustrate the analysis steps in typical Minitab software:

- Exploring data with graphs
- Conducting statistical analyses and procedures
- Assessing quality
- Designing an experiment
- Using shortcuts to automate future analyses
- Generating a report
- Preparing worksheets
- Customizing Minitab to fit your ne your needs
- Real-life data analysis situations
- Brief summaries of statistical capabilities
- Emphasis on important components of the output

CHAPTER 2

LITERATURE SURVEY

This chapter will be discussing the back ground studies related to the project. That is, the studies which focused on TIG butt welding, its parameters and limitations, and also the tensile strength of ductile materials, specifically that of mild steel.

Nabendu Ghosh, Pradip Kumar Palband, Goutam Nandic, in *Parametric Optimization of Gas metal arc welding process by PCA based Taguchi method on Austenitic Stainless Steel AISI 316L*, conducted visual inspection and X-ray radiographic tests in order to detect surface and sub-surface defects of weld specimens made of AISI 316L austenitic stainless steels. Effect of current, gas flow rate and nozzle to plate distance on quality of weld in metal inter gas arc welding of AISI 316L austenitic stainless steel has been studied in the present work through experiments and analyses. Butt welded joints have been made by using several levels of current, gas flow rate and nozzle to plate distance. The quality of the weld has been evaluated in terms of yield strength, ultimate tensile strength and percentage of elongation of the welded specimens. The observed data have been interpreted, discussed and analyzed by using Grey - Taguchi methodology.

Raghuvir Singh et al, in *Optimization of Process Parameters for TIG Welding of 304L Stainless Steel using Response Surface Methodology*, investigated the effect of TIG welding parameters like welding speed, current and flux on depth of penetration and width in welding of 304L stainless steel has been studied. From the study it was observed that flux used has the most significant effect on depth of penetration followed by welding current. However SiO₂ flux has more significant effect on depth. Optimization was done to maximize penetration and having less bead width.

Ugur Esme et al, in *Optimization of weld bead geometry in TIG welding process using grey relation analysis and Taguchi method*, investigated the multi-response optimization of tungsten inert gas welding (TIG) process for an optimal parametric combination to yield favorable bead geometry of welded joints using the Grey relational analysis and Taguchi method. Sixteen experimental runs based on an orthogonal array of Taguchi method were performed to derive objective functions to be optimized within experimental domain. The objective functions have been selected in relation to parameters

of TIG welding bead geometry, bead width, bead height, penetration, area of penetration as well as width of heat affected zone and tensile load. The Taguchi approach followed by Grey relational analysis was used to solve the multi-response optimization problem. The significance of the factors on overall quality characteristics of the weldment has also been evaluated quantitatively by the analysis of variance method (ANOVA). Optimal results have been verified through additional experiments. This shows application feasibility of the Grey relation analysis in combination with Taguchi technique for continuous improvement in product quality in manufacturing industry.

Amit P.Shinde, Abhijeet R.Deshpande, Satish S.Chinchanikar, and Atul P.Kulkarni in *Evaluation of Tensile Strength of a Butt-Welded Joint Considering the Effect of Welding Parameters Using Response Surface Methodology* proved that in this work, effect of welding parameters during metal inert gas welding (MIG) namely, welding current, flow rate of shielding gas and arc voltage is evaluated in terms of tensile and yield strength of butt-welded mild steel plates (IS 2062 Gr.E250, Quality A).MIG experiments were planned using Central Composite Rotatable Design (CCRD).Response Surface Methodology (RSM) technique was used to develop the correlations between the process variables and the responses. The correlation coefficients of developed multiple linear regression models found close to 0.9 indicate that the developed models are significant to predict the responses within the domain of process parameters selected in the present study. Study of analysis showed that ultimate tensile strength and yield strength are mostly affected by higher order of welding current and shielding gas flow rate. Results of optimization study showed that welding current of 170 ampere, shielding gas flow rate of 12 lpm (liter/min) and arc voltage of 24 V (volts) results in maximum values of tensile strength and yield strength of welded joint.

K.R.Jagtap, M.S.Rojekar, S.V.Dravid, and A.R.Deshpande in *Effect of Welding Parameters on Tensile & Yield Strength of IS 2062 grade Steel Using Design of Experiment Approach* carried out an experimental investigation through mathematical modeling to study the effect of welding current, feed rate, number of welding passes on tensile and yield strength during welding of IS 2062 E250 grade steel. The correlations between the welding parameters and performance measures like tensile strength, yield strength were established by multiple linear regression models. The correlation coefficients found close to 0.9 signifies

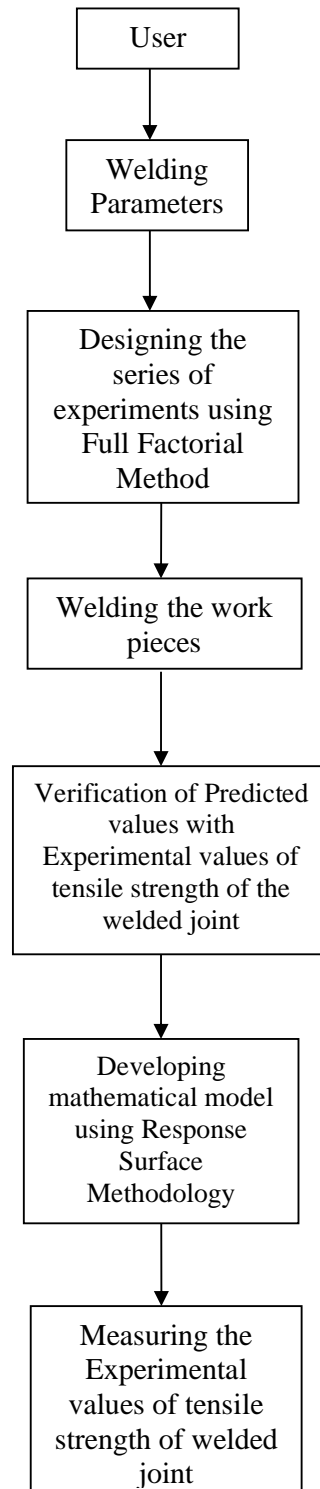
the reliability of the selected model. Hence the model can be effectively used for predicting the response within the domain of the welding parameters. Analysis of variance (ANOVA) was used to predict the impact of welding parameters on the response. Experimental observations show that tensile strength & yield strength mostly affected by a higher order of welding current & number of welding passes. Optimum welding parameters are determined using response surface methodology (RSM).

Hussain Zuhailawati, Muhammad Afiq Jamaluddin, Anasyida Abu Seman, Suhaina Ismail in *Welding Investigation and Prediction of Tensile Strength of 304 Stainless Steel Sheet Metal Joint by Response Surface Methodology* carried out an investigation of welding behaviour of 304 stainless steel sheet metal in term of joint strength and microstructure. Composition analysis of the stainless steel plate and ER308 filler rod was performed using X-ray fluorescence and SEM-EDX. Tungsten inert gas (TIG) welding was done on SS 304 2B plate with thick-ness of 1.2 mm in Coraza Systems Malaysia Sdn. Bhd using a KADEYOU machine. Response surface methodology (RSM) was employed to develop mathematical relationships between the welding process parameters (i.e, welding current, filler size and flow rate of the shielding gas) and the output variable of the weld joint (ultimate tensile strength) to determine the welding input parameters that led to the desired weld quality. Comparison between measured and calculated results was in good agreement indicating that the developed models can predict the responses adequately within the limits of welding parameters being used. High welding current caused microstructure to become finer and increase in tensile strength while low current caused root of the metal plate to not weld completely which weakened the joint.

CHAPTER 3

DESIGN OF EXPERIMENTS

3.1. METHODOLOGY



3.2. SELECTION OF MATERIAL

Austenitic stainless steel is most commonly used in petrochemical, chemical and power engineering, also in vehicle and aviation industries. Stainless steel is used when both the properties of steel and resistance to corrosion are required. The welding of automotive exhaust gas systems, stainless steel pipes, repairing of chemical industries' equipment etc., are done with the help of gas tungsten inert gas welding (GTAW or commonly known as TIG). Chrome-manganese austenitic stainless steel grades (standard 200-series) with well-defined and well-documented technical properties have proved acceptable materials for specific applications for many years. There has recently been a significant increase in the use of new and economical 696 Sahil Bharwal and Charit Vyas chrome manganese grades (which can be referred to as "new 200-series" grades). These 200-series grade use different chemistries, characterized by reduced chromium and extra low nickel content. As well as currently being significantly cheaper, from a material cost point of view, 200-series stainless steels can offer good strength, depending on their chemistry. Certain grades (equivalent to 201-, 202- and 205-series) even offer about 30% higher "mechanical properties" (yield strength) than the classic 304-series chrome nickel grade – allowing designers to cut weight. Almost the complete replacement of Nickel is possible by combined Manganese and Nitrogen addition with Carbon. Lower nickel addition requires more manganese and nitrogen to stabilize the austenitic phase. Higher draw ability properties may be obtained with lower nitrogen additions but then chromium content must be reduced down to 14-15% in order to provide the stability to the austenitic phase. AISI 304 stainless steel is widely used in forming applications because of its superior formability. The high nickel price in recent years prompted an investigation into the feasibility of replacing AISI 304 with AISI 202 in applications requiring comparable mechanical properties.

The aim of this investigation was therefore to study the weldability of AISI 202 stainless steel using uniaxial tensile tests. A huge rectangular slab of Stainless Steel SS 202 was cut into 18 pieces in order to get 9 welded joints. Material used is shown in Fig 3.1.

The size of work piece used is $160*50*4.5 \text{ mm}^3$

The length of weld is 50 mm



Fig. 3.1 Flat specimen of Stainless Steel SS 202 used for experimentation

Table 3.1. Chemical composition of Stainless Steel SS 202

Element	Percentage of weight
Carbon	0.065
Silicon	0.373
Manganese	8.131
Sulphur	0.007
Phosphorus	0.012
Chromium	17.310
Nickel	4.380
Molybdenum	0.272
Copper	0.194
Aluminum	0.000
Titanium	0.005
Vanadium	0.057
Cobalt	0.026
Niobium	0.020
Wolfram	0.012
Iron	68.842

Table 3.2. Physical properties of Stainless Steel SS 202

Property	Value
Density	$7.8 \times 10^3 \text{ kg/m}^3$
Poisson's Ratio	0.27-0.30
Elastic Modulus	190-210 GPa
Tensile Strength	515 MPa
Yield Strength	275 MPa
Elongation	40 %

3.3. EQUIPMENTS USED

The work pieces were made initially by cutting them in workshop using workshop tools. The cut work pieces were butt-welded using “TIG welding equipment” as shown in Fig 3.2. The welded work pieces (Fig 3.3) were then cut again into the shape of “dumbbells” (Fig 3.1). These dumbbell shaped flat specimens (Fig 3.1) were tested for tensile strength using “Universal Testing machine (UTM)”, as shown in Fig 3.4.

**Fig. 3.2** TIG Welding Equipment



Fig. 3.3 Initial welded specimen



Fig. 3.4 Flat specimen undergoing tensile testing in UTM machine

3.4. PROCESS VARIABLES USED IN EXPERIMENTATION

The input welding parameters selected were:

- Welding Current (I)
- Gas Flow Rate (GF)
- Filler Rod Diameter (FD)

Table 3.3. Process variables used in experiment

S. No.	Parameters	Level I	Level II	Level III
1	Current (I) Amps	90	100	110
2	Gas flow rate (GF) mm³/sec	12	14	16
3	Fillet rod diameter (FD) mm	1.6	2.0	2.5

3.5. OUTPUT VALUES OBTAINED

In order to obtain the output values of “Tensile Strength”, two practical processes are done in the total experiment.

- TIG Welding of workpieces
- Tensile test on Ultimate tensile testing machine

3.5.1. Welding process

Initially, after machining the work pieces to required length, one of the edges is filed to form an inclined edge. This is done in order to butt-weld 2 pieces.

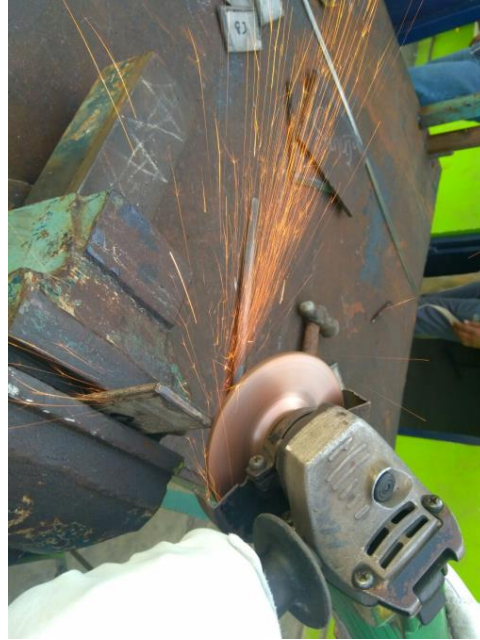


Fig. 3.5 Preparation of workpiece

The two rectangular specimens shown in Fig. 3.6 are butt-welded together using TIG Welding equipment shown in Fig. 3.2. The welded specimen is shown in Fig 3.3. Then, for the purpose of tensile testing, the rectangular specimen is cut into a dumbbell shaped flat specimen as shown in Fig. 3.1.



Fig. 3.6 Workpieces readied for Butt welding

3.5.2. Tensile testing

Using the equipment shown in Fig. 3.4, the flat specimen shown in Fig. 3.1 is tested for Tensile strength. The resultant Tensile strength values are notes in the Table 3.4.

Table 3.4. Output values obtained

S. No.	Current (I) Amps	Gas Flow Rate (GF) mm ³ /sec	Filler Rod Diameter (FD) mm	Tensile strength (TS) kN/mm ²
1	90	12	1.6	61
2	90	14	2.0	56.5
3	90	16	2.5	62.5
4	100	12	2.0	58.5
5	100	14	2.5	63
6	100	16	1.6	51.5
7	110	12	2.5	63.5
8	110	14	2.0	63.5
9	110	16	1.6	59

3.6. DESIGN OF EXPERIMENTS

3.6.1. Introduction to Design of Experiments

“Design of Experiments” is an experimental or analytical method that is commonly used to statistically signify the relationship between input parameters and output responses. DOE has a wide range of applications, especially in the field of science and engineering for the purpose of process optimization and development, process management and validation tests. DOE is essentially an experimental based modeling and is a designed experimental approach which is far superior to unplanned approach, whereby, a systematic way will be used to plan the experiment, collect the data and analyze the data. A mathematical model has been developed by using analysis techniques such as ANOVA and regression analysis whereby the mathematical model shows the relationship between the input parameters and the output responses. Among the most prominently used DOE techniques are Response Surface Methodology with Central Composite Design, Taguchi’s method and Factorial Design. In DOE, synergy between mathematical and statistical techniques such as Regression, Analysis of Variance (ANOVA), Non-Linear Optimization and Desirability

functions helps to optimize the quality characteristics considered in a DOE under a cost effective process. ANOVA helps to identify each factor effect versus the objective function.

Experimental design was first introduced in the 1920s by R. A. Fischer working at the agricultural field station at Rothamsted in England. Fischer was concerned with arranging trials of fertilizers on plants to protect them against the underlying effect of moisture, gradient, nature of soils, etc. Fischer developed the basic principles of factorial design and the associated data analysis known as ANOVA during research in improving the yield of agricultural crops.

3.6.2. Advantages & Disadvantages of DOE

DOE became a more widely used modeling technique superseding its predecessor one-factor-at- time (OFAT) technique. One of the main advantages of DOE is that it shows the relationship between parameters and responses. In other words, DOE shows the interaction between variables which in turn allows us to focus on controlling important parameters to obtain the best responses. DOE also can provide us with the most optimal setting of parametric values to find the best possible output characteristics. Apart from that, the mathematical model generated can be used as a prediction model which can predict the possible output responses based on the input values. Another main reason DOE is used because it saves time and cost in terms of experimentation. DOE functions in such a manner that the number of experiments or the number of runs is determined before the actual experimentation is done. This way, time and cost can be saved as we do not have to repeat unnecessary experiment runs. Usually, experiments will have errors occurring. Some of them might be predictable while some errors are just out of control. DOE allows us to handle these errors while still continuing with the analysis. DOE is excellent when it comes to prediction of linear behavior. However, when it comes to nonlinear behavior, DOE does not always give the best results.

3.7. FACTORIAL METHOD

Factorial designs allow for the simultaneous study of the effects that several factors may have on a process. When performing an experiment, varying the levels of the factors simultaneously rather than one at a time is efficient in terms of time and cost, and also allows for the study of interactions between the factors. Interactions are the driving force in many

processes. Without the use of factorial experiments, important interactions may remain undetected.

Different types of designs available in Factorial Method

- Two-level full factorial designs
- Two-level fractional factorial designs
- Plackett-Burman designs
- General full factorial designs

3.8. FRACTIONAL FACTORIAL METHOD

A fractional design is a design in which experimenters conduct only a selected subset or "fraction" of the runs in the full factorial design. Fractional factorial designs are a good choice when resources are limited or the number of factors in the design is large because they use fewer runs than the full factorial designs. A fractional factorial design uses a subset of a full factorial design, so some of the main effects and 2-way interactions are confounded and cannot be separated from the effects of other higher-order interactions. Usually experimenters are willing to assume the higher-order effects are negligible in order to achieve information about main effects and low-order interactions with fewer runs.

3.8.1. Using Minitab to Run a Fractional Factorial Experiment

1. Initiate the experiment design.

- Click Stat → DOE → Factorial → Create Factorial Design.
- A new window named "Create Factorial Design" pops up.
- Select the radio button "2-level factorial (default generators)."
- Enter "3" as the "Number of factors."

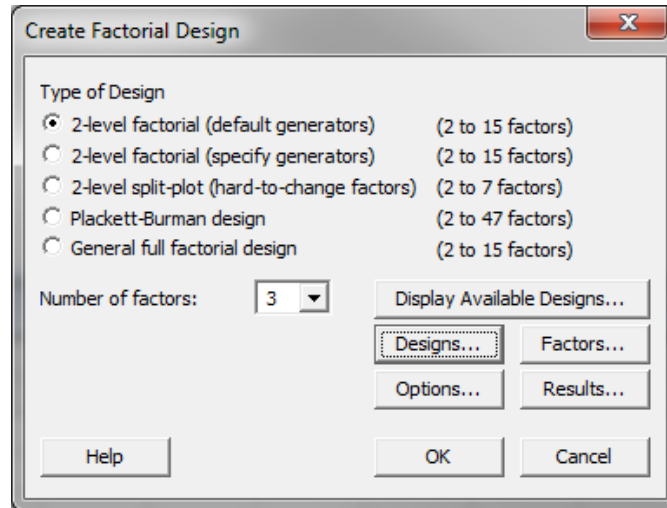


Fig. 3.7 Creating Factorial Design

- Click on the “Design” button in the window “Create Factorial Design” and another new window named “Create Factorial Design – Designs” pops up.
- Highlight the “1/2 fraction” design in the box.
- Select “2” as the “Number of replicates for corner points.”

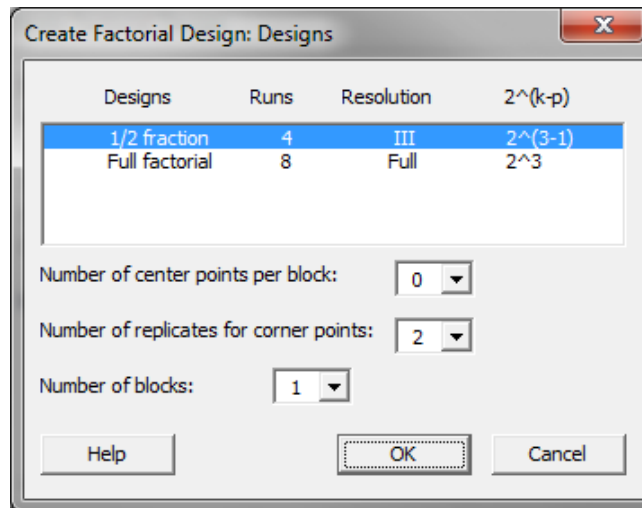


Fig. 3.8 Selecting fractional factorial design

- Click “OK” in the window “Create Factorial Design – Designs.”
- Click “OK” in the window “Create Factorial Design.”

The design table is created in the data table.

- Click on the “Factors” button in the window “Create Factorial Design” and a new window named “Create Factorial Design – Factors” appears.

- Enter the names and the levels for individual factors. In this example, we keep the default names and levels for factors A, B, and C.

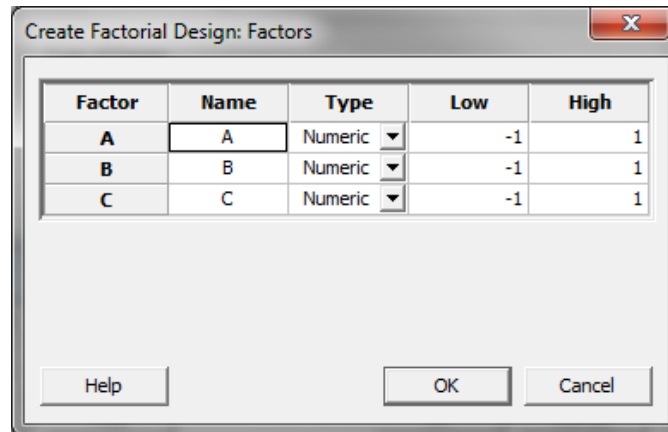


Fig. 3.9 Factors in a factorial design

2. Implement the experiment and record the results in the DOE table.
3. Fit the model using the experiment results.
4. Analyze the model results.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. ANALYSIS OF VARIANCE

In statistics, analysis of variance (ANOVA) is a collection of statistical models, and their associated procedures, in which the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are all equal, and therefore generalizes t-test to more than two groups. Doing multiple two-sample t-tests would result in an increased chance of committing a type I error. For this reason, ANOVAs are useful in comparing three, or more means.

4.1.1. Characteristics of ANOVA

ANOVA is used in the analysis of comparative experiments, those in which only the difference in outcomes is of interest. The statistical significance of the experiment is determined by a ratio of two variances. This ratio is independent of several possible alterations to the experimental observations: Adding a constant to all observations does not alter significance. Multiplying all observations by a constant does not alter significance. So ANOVA statistical significance results are independent of constant bias and scaling errors as well as the units used in expressing observations.

4.2. MATHEMATICAL MODELING

4.2.1. Linear Regression equation:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k$$

4.2.2. Multiple linear regression equation:

Multiple linear regression equation is a second order polynomial equation of the form –

$$Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \epsilon$$

Where,

Y is the corresponding response

$(1, 2, \dots, S)$ are coded levels of S quantitative process variables

The terms are the second order regression coefficients

Second term is attributable to linear effect

Third term corresponds to the higher-order effects

Fourth term includes the interactive effects

The last term indicates the experimental error

4.3. TERMS & GRAPHS IN RESPONSE SURFACE METHODOLOGY

4.3.1. Regression table

1. P-values

P-values (P) are used to determine which of the effects in the model are statistically significant.

- If the p-value is less than or equal to α (0.05), conclude that the effect is significant.
- If the p-value is greater than α , conclude that the effect is not significant.

2. Coefficients

Coefficients are used to construct an equation representing the relationship between the response and the factors.

3. R-squared

R^2 and adjusted R^2 represent the proportion of variation in the response that is explained by the model.

- R^2 (R -Sq) describes the amount of variation in the observed responses that is explained by the model.
- Predicted R^2 reflects how well the model will predict future data.

- Adjusted R^2 is a modified R^2 that has been adjusted for the number of terms in the model. If we include unnecessary terms, R^2 can be artificially high. Unlike R^2 , adjusted R^2 may get smaller when we add terms to the model.

4. Analysis of variance table

P-values (P) are used in analysis of variance table to determine which of the effects in the model are statistically significant. The interaction effects in the model are observed first because a significant interaction will influence the main effects.

5. Estimated coefficients using uncoded units

Minitab displays the coefficients in uncoded units in addition to coded units if the two units differ.

For each term in the model, there is a coefficient. These coefficients are useful to construct an equation representing the relationship between the response and the factors

4.3.2. Graphs

1. Histogram of residuals

Histogram of the residuals shows the distribution of the residuals for all observations

2. Normal plot of residuals

Graph is plotted between the residuals versus their expected values when the distribution is normal. The residuals from the analysis should be normally distributed. In practice, for balanced or nearly balanced designs or for data with a large number of observations, moderate departures from normality do not seriously affect the results. The normal probability plot of the residuals should roughly follow a straight line.

3. Residuals versus fits

Graph is plotted between the residuals versus the fitted values. The residuals should be scattered randomly about zero.

4. Residuals versus order

This graph plots the residuals in the order of the corresponding observations. The plot is useful when the order of the observations may influence the results, which can occur when data are collected in a time sequence or in some other sequence. This plot can be particularly helpful in a designed experiment in which the runs are not randomized.

4.4. ANALYSIS OF VARIANCE FOR TENSILE STRENGTH

Table 4.1. ANOVA of Tensile strength

Source	DF	Adj SS	Adj MS	F value	P value
Model	6	111.170	18.5283	2.15	0.351
Linear	3	75.260	25.0867	2.91	0.266
I	1	34.713	34.7133	4.03	0.182
GF	1	1.698	1.6980	0.20	0.700
FD	1	3.136	3.1363	0.36	0.607
2 way interactions	3	57.669	19.2229	2.23	0.324
I*GF	1	4.969	4.9687	0.58	0.527
I*FD	1	0.961	0.9610	0.11	0.770
GF*FD	1	32.722	32.7223	3.80	0.191
Error	2	17.219	8.6096		
Total	8	128.389			

S = 2.93422

R-sq = 86.59%

R-sq(adj) = 46.35%

R-sq(pred) = 0.00%

4.4.1. Regression Equation

The mathematical relationship for correlating the Tensile strength and the considered process variables has been obtained as follows

$$\text{Tensile Strength} = 105 + 1.46 I - 3.2 GF - 113 FD - 0.108 I*GF + 0.227 I*FD + 6.64 GF*FD$$

Where,

I = Current

GF = Gas Flow Rate

FD = Filler Rod Diameter

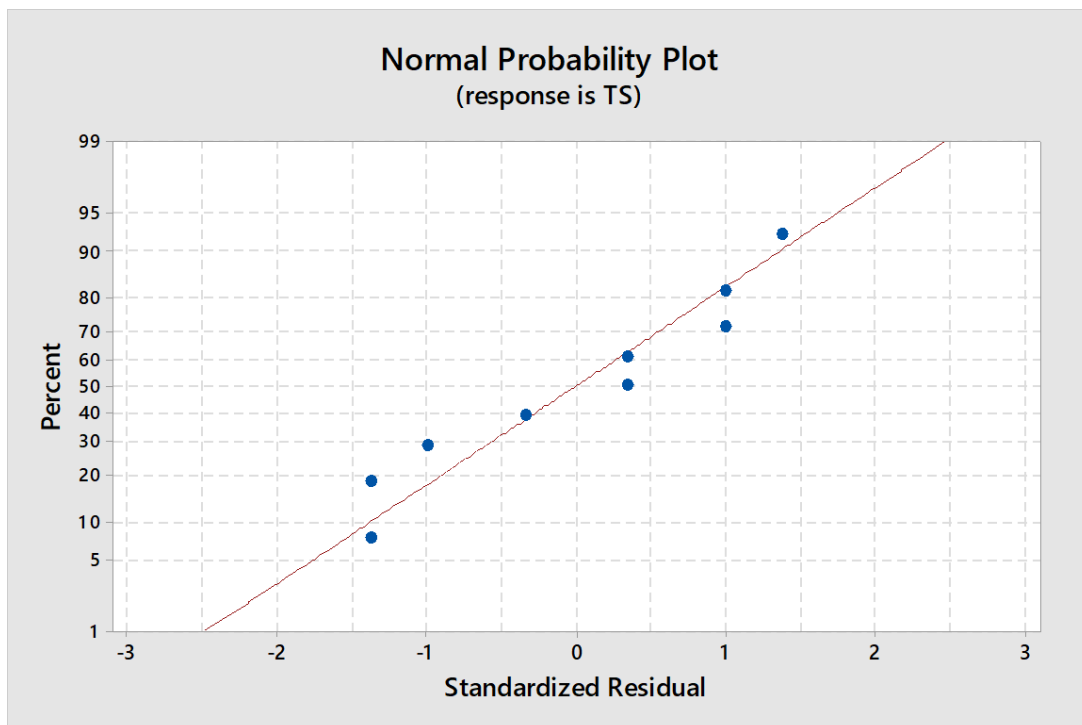
The second-order polynomial models are developed for Tensile Strength. The fit summary indicates that the quadratic model is statistically significant for analysis of Tool life.

4.5. Graphs

4.5.1. Normal probability plot for tool life

The normal probability plot, shows a clear pattern (as the points are almost in a straight line) indicating that all the factors and their interactions given are effecting the tensile strength. In addition, the errors are normally distributed and the regression model is well fitted with the observed values.

Pattern	Indication
Not a straight line	Non normality
Curve in the tails	Skewness
A point far away from the line	Outlier
Changing slope	Unidentified variable



Minitab provides three types of residuals:

Regular residual: observed value - predicted value.

Standardized residual: $\frac{(\text{Observed value} - \text{Predicted value})}{\text{Predicted value}}$

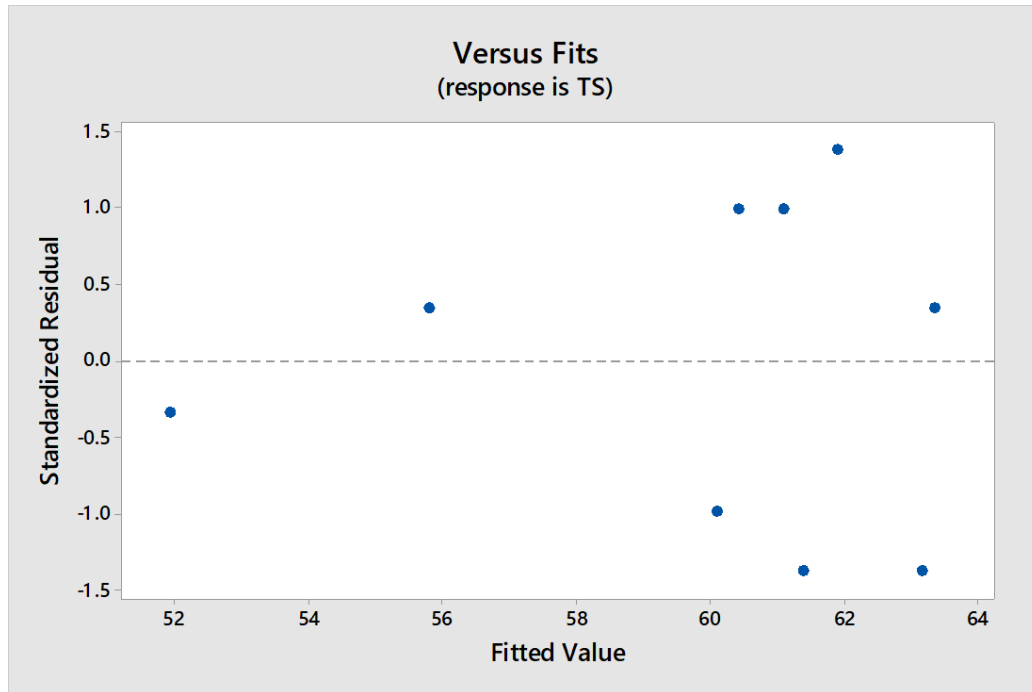
The standardization eliminates the effect of the location of the data point with respect to the predictors or factors.

Studentized deleted residual: For the i^{th} data point, the formula follows the same expression as the standardized residual. However, the i^{th} fitted value and the standard deviation are calculated for the studentized deleted residual by deleting the i^{th} case in the analysis. Compared to the standardized residual, the studentized deleted residual becomes larger in the presence of an unusual data point.

4.5.2. Standardized residual vs Fits plot

Graph indicates that the maximum variation of 0 to 200, which shows the high correlation that, exists between fitted values and observed values.

Pattern	Indication
Fanning/uneven spreading of residuals across fitted values	Non-constant variance
Curvilinear	A missing higher order term
A point far away from zero	An outlier
A point far away from the other points in the x-direction	An-influential point

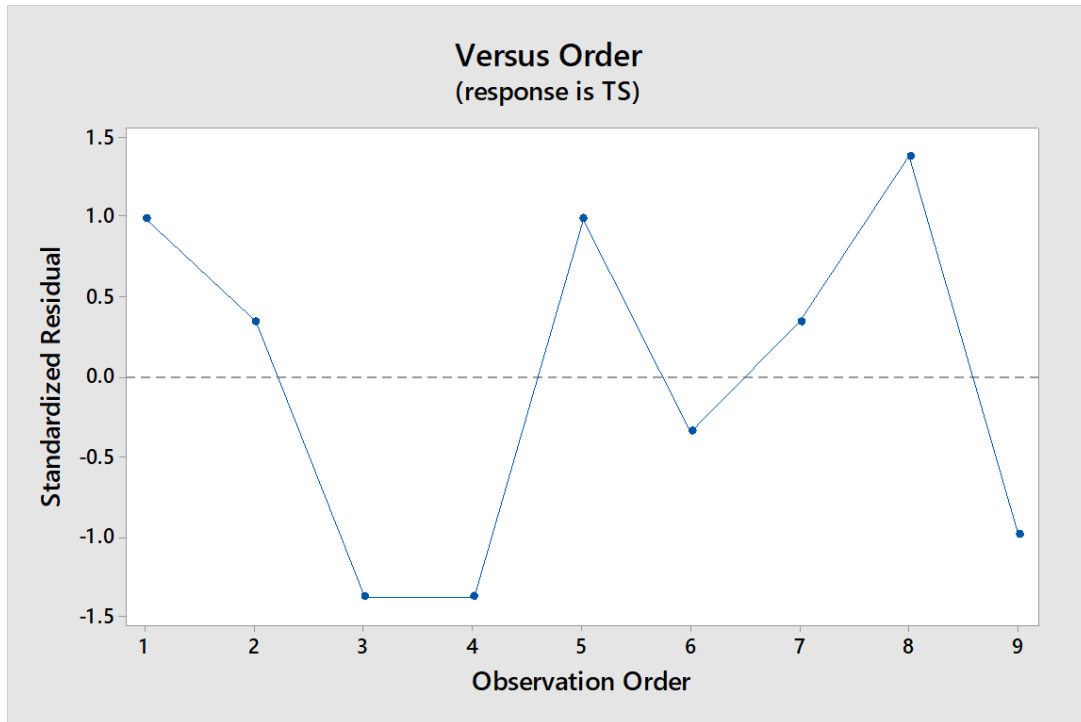


4.5.3. Residuals vs Order plot

This graph plots the residuals in the order of the corresponding observations. The plot is useful when the order of the observations may influence the results, which can occur when data are collected in a time sequence or in some other sequence. This plot can be particularly helpful in a designed experiment in which the runs are not randomized.

Correlation among residuals may be signified by:

- An ascending or descending trend in the residuals
- Rapid changes in signs of adjacent residuals

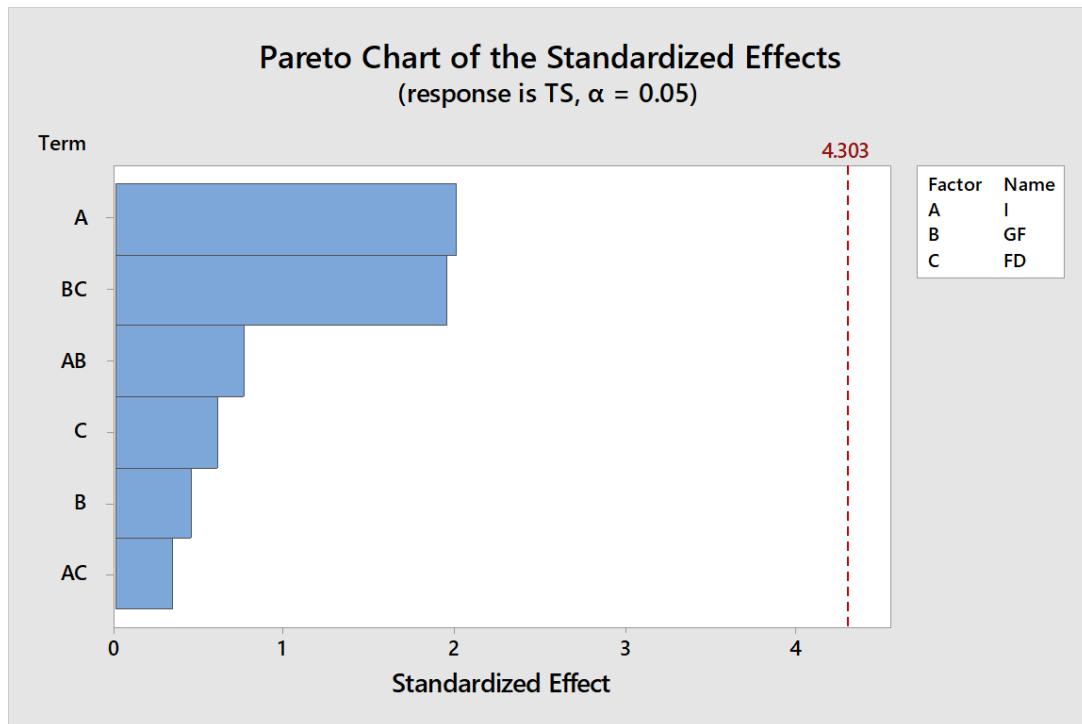


4.5.4. Pareto Chart of the Standardized effects

A Pareto chart is a bar graph. The lengths of the bars represent frequency or cost (time or money), and are arranged with longest bars on the left or top and the shortest to the right or bottom. In this way the chart visually depicts which situations are more significant.

A Pareto Chart is used -

- When analyzing data about the frequency of problems or causes in a process.
- When there are many problems or causes and you want to focus on the most significant.
- When analyzing broad causes by looking at their specific components.
- When communicating with others about your data.



It can be seen from the obtained Pareto chart that Term A, which represent Current, has the most significant effect on the output, Tensile strength. It is followed by a product of terms B and C, which is the product of Gas flow rate and Filler rod diameter. The least significant effect on Tensile strength is by the product of terms A and C, i.e., the product of current and filler rod diameter.

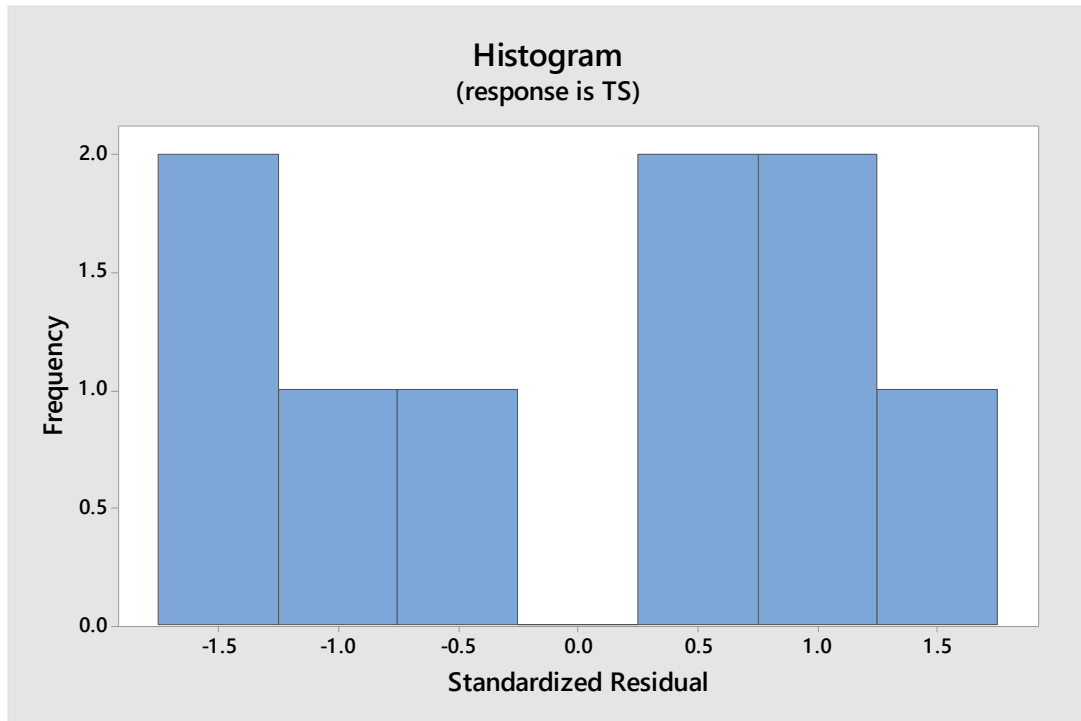
4.5.5. Histogram

A frequency distribution shows how often each different value in a set of data occurs. A histogram is the most commonly used graph to show frequency distributions. It looks very much like a bar chart, but there are important differences between them.

A Histogram is used -

- When the data are numerical.
- When you want to see the shape of the data's distribution, especially when determining whether the output of a process is distributed approximately normally.
- When analyzing whether a process can meet the customer's requirements.
- When analyzing what the output from a supplier's process looks like.

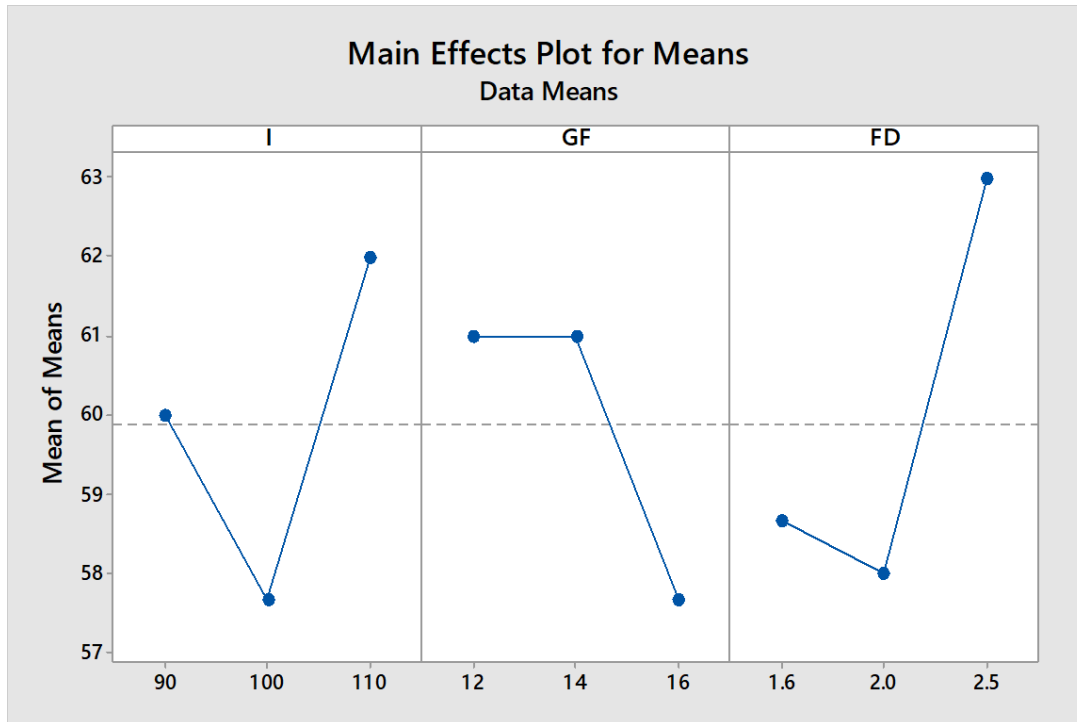
- When seeing whether a process change has occurred from one time period to another.
- When determining whether the outputs of two or more processes are different.
- When you wish to communicate the distribution of data quickly and easily to others.



4.5.6. Main effect and Interaction plots

Minitab creates the main effects plot by plotting the means for each value of a categorical variable. A line connects the points for each variable. Look at the line to determine whether a main effect is present for a categorical variable. Minitab also draws a reference line at the overall mean. Interpret the line that connects the means as follows:

- When the line is horizontal (parallel to the x-axis), there is no main effect present. The response mean is the same across all factor levels.
- When the line is not horizontal, there is a main effect present. The response mean is not the same across all factor levels. The steeper the slope of the line, the greater the magnitude of the main effect.



4.6. Predicted and experimental values

The mathematical relationship for correlating the Tensile strength and the considered process variables has been obtained as follows –

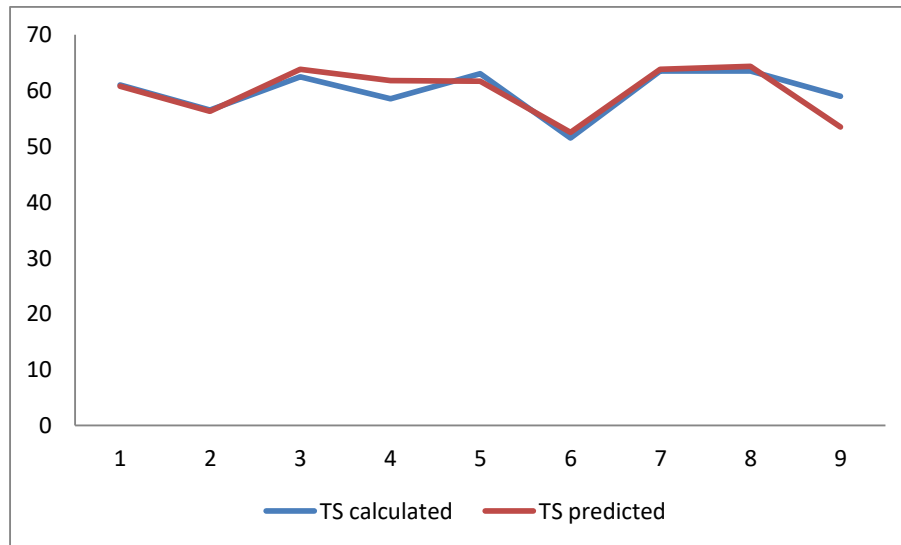
$$\begin{aligned} \text{Tensile Strength} = & 105 + 1.46 I - 3.2 GF - 113 FD - 0.108 I*GF + 0.227 I*FD \\ & + 6.64 GF*FD \end{aligned}$$

The above equation is used to calculate the predicted values of the experiment. The values so obtained are compared with the obtained experimental values of Tensile strength.

Table 4.2. Predicted and Experimental values of Tensile strength

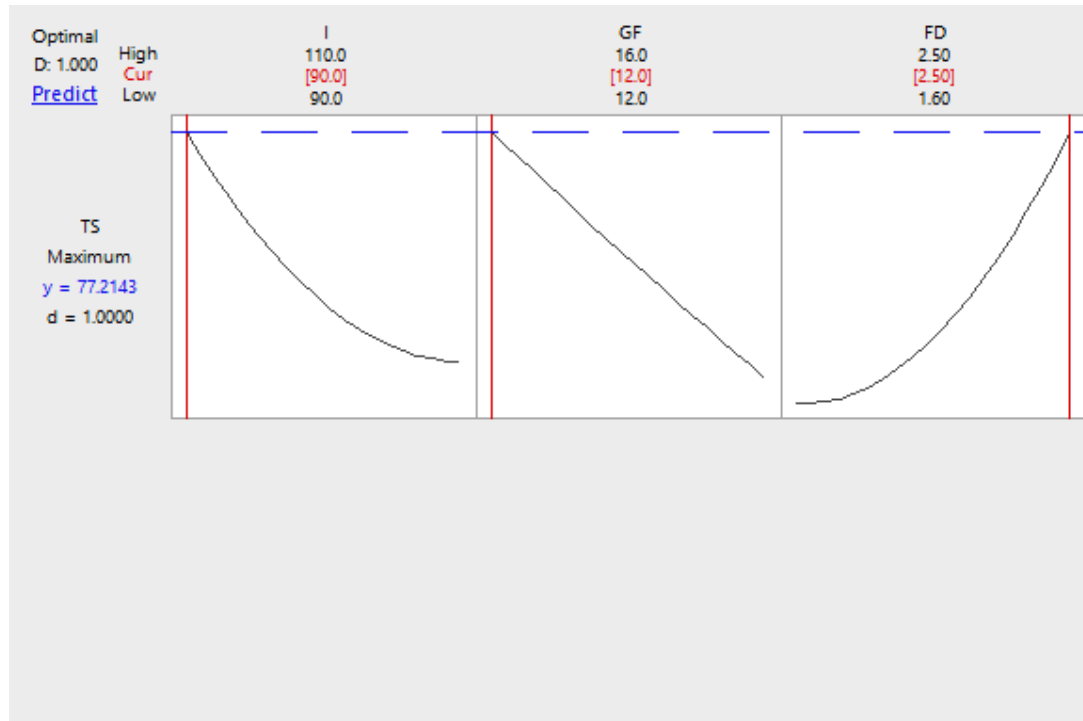
S. No.	Current (Amps)	Gas Flow Rate (mm ³ /sec)	Filler Rod Diameter (mm)	Tensile strength predicted (kN/mm ²)	Tensile strength calculated (kN/mm ²)	Error (%)
1	90	12	1.6	60.7360	61	0.432787
2	90	14	2.0	56.3000	56.5	0.353982
3	90	16	2.5	63.8550	62.5	2.168
4	100	12	2.0	61.7600	58.5	5.57265
5	100	14	2.5	61.6500	63	2.142857
6	100	16	1.6	52.5040	51.5	1.949515
7	110	12	2.5	63.7650	63.5	0.417323
8	110	14	2.0	64.3400	63.5	1.322835
9	110	16	1.6	53.4560	59	9.39661

The nearness or the variation of experimental value with respect to the predicted value can be seen the graph below -



4.7. Optimization Plot

A Minitab Response Optimizer tool shows how different experimental settings affect the predicted responses for factorial, response surface, and mixture designs. Minitab calculates an optimal solution and draws the plot. The optimal solution serves as the starting point for the plot. This optimization plot allows to interactively changing the input variable settings to perform sensitivity analysis and possibly improve the initial solution.



The optimization plot shows the effect of each factor (columns) on the responses or composite desirability (rows). The vertical red lines on the graph represent the current factor settings. The numbers displayed at the top of a column show the current factor level settings (in red). The horizontal blue lines and numbers represent the responses for the current factor level.

Minitab calculates that tensile strength is maximized when all the factors are at their lowest levels i.e. when current, gas flow rate, and filler rod diameter are at their lowest levels.

From the above Optimization plot, the following can be said –

Maximum Tensile Strength = 77.2143 kN/mm^2

Obtained when,

Current (I) = 90 Amps

Gas flow rate (GF) = $12 \text{ mm}^3/\text{sec}$

Filler rod diameter (FD) = 1.60 mm

CHAPTER 5

SUMMARY

5.1. CONCLUSION

5.2. FUTURE SCOPE

CHAPTER 6**REFERENCES**

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