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Statistical Analysis of Welding Parameters Affecting the Tensile Strength of Mild Steel Plates

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Abstract

This study is aimed at using various statistical analyses within the Design of Experiments (DOE) technique to investigate and analyze the effect of welding process parameters on the tensile strength of A36-grade mild steel. Three process parameters and two corresponding levels were considered and the MIG welding process was performed. The ideal conditions to achieve the highest strength were determined and the results were obtained by running the design on a statistical software Minitab. This experimental study found that the only factor having a significant contribution to the tensile stress of the plates in the selected scenario is the weld speed. In addition, this study provides valuable insights for enhancing welding procedures and techniques. The paper concludes with a reasonable interpretation of the test results and justifies the research questions that were proposed.

Keywords

MIG welding, ANOVA, Minitab, Tensile Strength, DOE.

1. Introduction

Welding processes are used in various industries such as manufacturing, construction, automotive, and aerospace. The strength of the welded material is of immense importance as it directly indicates the overall quality of the parts produced. A failing welded part can not only cause huge losses to manufacturers but can also compromise the safety of end users. A good quality weld can always help with product durability and longevity. A statistical methodology such as DOE can be incorporated to optimize the welding parameters and establish the preferred quality and strength.

Process and quality improvement tools especially utilizing lean and Six Sigma concepts are widely used in both manufacturing and service sectors (Freimut et al., 2005; Soković et al., 2009; Verma et al., 2021; Alblooshi et al., 2022; Bader et al., 2020; Badiru, 2005; Bhandari et al., 2021; Soltani and Bhandari 2023; Bartlett et al., 2023; Verma et al., 2022). Design of Experiments (DOE) is a powerful technique that is often used as an applied statistical tool that deals with planning, conducting, analyzing, and interpreting controlled experiments in a laboratory to explore and evaluate the factors that control the value of a factor or various factors (Bower, 2023). This technique can be used in various situations including but not limited to improving processes and systems, understanding the relationship between the response variable and different factors, and identifying factors that significantly impact the outcome of the response variable (Srebrenkoska et al., 2016; Walston et al., 2022).

DOE is also a systemic approach to studying cause-and-effect relationships. Technology commercialization and product realization operations, such as new product design and formulation, manufacturing process development, and process improvement, all heavily rely on experimentation (Montgomery, 2017). DOE helps predict the changes in input variables, also known as factors, onto the output variable, the response variable. DOE also helps in identifying the crucial interaction effects and takes into account all the possible combinations of factors considered in the experiment (Anderson & Whitcomb, 2017).

Powerful and dynamic statistical software like Minitab is most suited to experiments with large amounts of data. The program interface is designed to be simple and user-friendly. In addition to the tools required to design and analyze experiments, Minitab supports most of the other statistical analyses and methods such as basic descriptive and inferential statistics, SPC, reliability, Gage R&R studies, and many more (Mathews, 2004).

The combination of these various tools and techniques gives businesses methodical ways to improve their operations, output, and customer service. These advancements enable focused improvements by first assisting in the identification and analysis of inefficient or defective areas. Secondly, they facilitate data collection and analysis for companies, providing a quantitative basis for decision-making and performance evaluation. This approach promotes a culture of continuous improvement by encouraging teams to actively look for methods to improve their work. Problem-solving is made easier by providing organized techniques for identifying the core issues and putting a solution in place. Companies can gain a competitive advantage, enhanced efficiency, and a greater level of customer satisfaction by consistently employing quality improvement methods (Ahmed et al., 1999).

1.1 Research Questions

RQ1. Out of the three vital factors selected for this DOE study, which one has the most significant effect on the response variable?
RQ2. What are the optimal values of the welding process parameters in order to achieve the highest tensile stress of the plates?
RQ3. Why is it necessary to train novice welders about weld quality?

1.2 Objectives

The study followed a step-by-step experimentation process along with the numerical and graphical analysis of the data obtained from running the design on the Minitab Statistical Software.

1.2.1 2^3 Factorial Design

This study used a three-factor, 2 level approach wherein three independent variables and their corresponding factors were utilized.

1.2.2 16 runs

The 2^3 will have 8 runs and we will be using two replicates in order to remove variability and bias. Therefore, a total of 16 runs will be performed for this experiment.

1.2.3 Most significant factor affecting Tensile Stress

The results from Minitab gave valuable insights into the study and helped establish a clear link in identifying the most important variables that have an impact on the selected response variable.

1.2.4 Ideal Welding Conditions Using Response Optimization

The Response Optimizer tool in Minitab was utilized to obtain the ideal welding parameters that maximize the value of our response variable.

1.2.5 Significance of Training of Novice Welders

The importance of weld quality and the necessity for training novice welders will be justified at the end of this study.

2. Literature Review

Welding is a fabrication process in which two metals are joined together by the application of heat and filler material. In ancient times, this process was used to modify iron into useful shapes. Today, it is used in several industries like construction, automotive, metalworking, etc. Technological advancements in the field have given rise to various welding techniques such as Tungsten Inert Gas (TIG) welding, Metal Inert Gas (MIG) welding, Submerged Arc welding, Oxy-Acetylene welding, etc.

In the MIG welding process, an electric arc forms between the consumable wire electrode and the workpiece metal. The heat generated by the arc causes the workpiece to melt and then solidify later, to form the joint. The process also uses a shielding gas (compressed argon), to keep the weld bead safe from hydrogen and nitrogen present in the atmosphere. Due to its comparatively low cost, enhanced productivity, ease of multi-dimensional welding, and robustness in its application to numerous metallic properties, MIG welding has gained large traction. The quality of welds is determined by several parameters throughout the MIG Welding process, some influencing elements include the metallurgical characteristics, bead shape, and weld chemistry. As a consequence, welding input parameters such as welding current, welding voltage, travel speed, gas flow rate, etc. have a major impact on these properties (Baloyi et al., 2021).

Mild steel is the most widely used structural steel, especially for welding operations. This experiment will be done on A36 grade mild steel, which is also known as ASTM A36 steel. In comparison to other steels, it has a negligible percentage of additional alloy elements outside iron, which improves its weldability, machinability, and toughness (Ikumapayi et al., 2021). It is the most commonly utilized grade of steel in construction, manufacturing, and a variety of engineering applications due to its versatility and relatively low cost (Aayola et al., 2023).

Tensile Stress (also known as tensile strength, or Ultimate Tensile strength) is the maximum load a material can withstand before it breaks. The force is applied in the opposite direction from both ends of the material. It is a critical factor in designing structures and components made of steel. It also helps in determining the load-bearing capacity of steel and aids failure analysis, investigations, and improvement of safety against crash impact and blast loads (Singh et al., 2013).

The graph of the stress-strain curve (Figure 1) illustrates how stress changes as the strain rises. It is a commonly used reference graph for metals, mainly in material science and industries. The Ultimate strength (U) is the variable that we are interested in observing.

When the steel plates are subjected to tensile load, the stress-strain behavior exhibits a linear curve between the origin to the proportional limit point, where stress is directly proportional to strain. Beyond this point, the proportionality no longer exists. From the elastic limit to the yield point, there is a considerable increase in strain without much increase in stress, which is because of plastic deformation that occurs in the metal. The region between the yield point and the ultimate tensile strength is known as strain hardening. This is where more stress is required to produce plastic deformation. The load eventually reaches its maximum value here, which is known as the ultimate strength or the ultimate tensile strength. Further stretching of metal beyond this point leads to a decrease in cross-sectional area. This reduction in a localized area is termed as necking. The metal finally breaks at the fracture point.

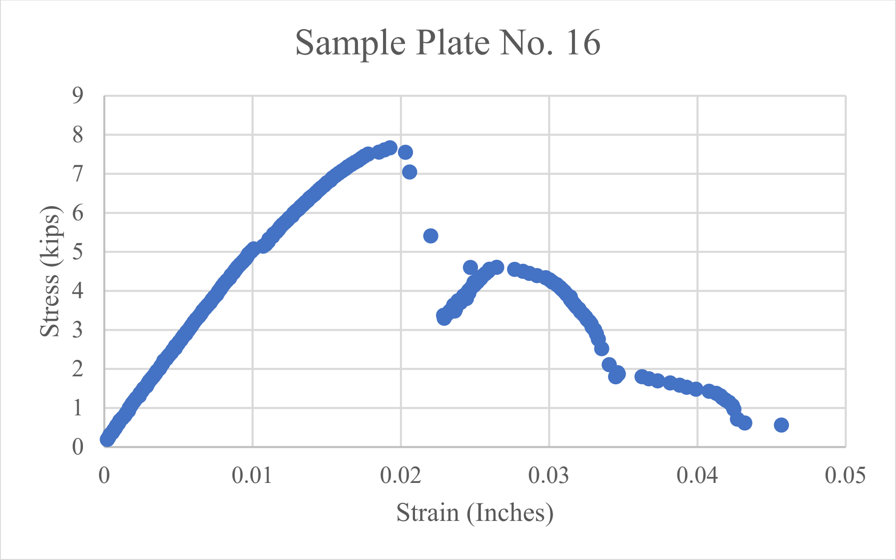


Figure 1. Stress-strain behavior observed in the experiment

3. Methods

3.1 Destructive Testing (Tensile Test)

This method of testing involves subjecting the test metal to a level of load or stress that causes permanent deformation. There are various types of destructive testing namely tensile testing, compression testing, impact testing, etc.

Tensile testing was performed for this study using the universal testing machine. In this test, the metal specimen is subjected to axial stress from opposite sides. It is particularly helpful in obtaining information about yield strength, tensile strength, and ductility of the metallic material. It measures the force required to break the metal specimen and also helps depict the extent to which it elongates before breaking point (Saba et al., 2019).

A typical testing specimen is shown above, which has enlarged shoulders for gripping. The force is applied to either end and the gage length section is the area of focus as the deformation and failure will be localized in this region. In order to prevent the bigger ends from restricting deformation with the gage section, there should be ample space between the ends of the gage section and the shoulders. If not, there will be more going on in the stress state than simple tension.

3.2 Materials and Equipment Used

3.2.1. A36 Grade Low Carbon Steel Plates

32 pieces, 2 for each run
Length: 4-inch, Thickness: 1/8-inch, Width: 1½ inch (Figure 2)

Figure 2. A36 Mild Steel Plate

3.2.2. Millermatic 200 Mig Welder (Figure 3)

- 10-ft. (3 m) MDX™-250 MIG gun
- 13-ft. (4 m) lead with electrode holder and 25-mm Dinse connector
- 10-ft. (3 m) work lead with clamp and 25-mm Dinse connector
- Argon and AR/CO2 mix regulator/flow gauge with 12-ft. (3.7 m) hose
- Power cord and MVP plugs for 120 and 240 V

Figure 3. Millermatic 200 MIG Welder Machine in the lab

3.2.3. MTS 810 Material Test System (Figure 4)

- Maximum force 15 kN and 100 kN
- Type Hydraulic
- Maximum testing range 150 mm
- Standards DIN and ISO

Figure 4. MTS Tensile Testing Machine in the lab

3.3 Choice of Factors and Levels

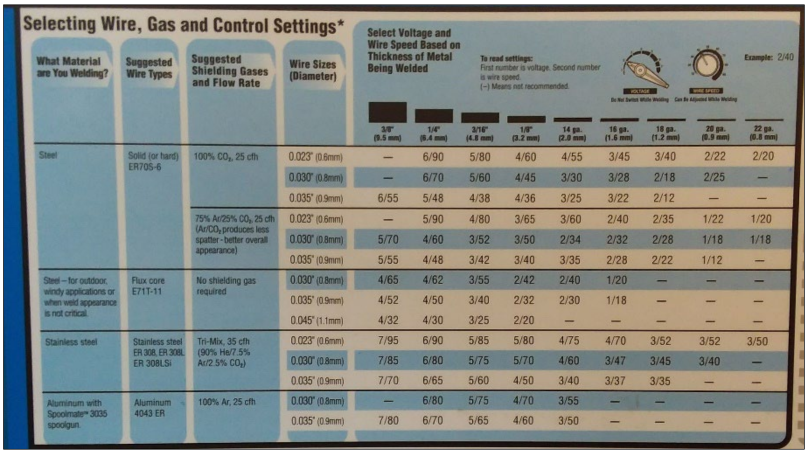
The experiment involved three factors and two levels. The response variable is the Tensile Stress of the plates. These parameters were chosen due to their practical significance, ease of optimization, and industry norms. The welding parameters are very critical to the welding process, hence the variations in these process parameters will help us understand the sensitivity of the welding process. The wire speed, voltage setting, and travel speed are easily accessible and can be controlled conveniently while welding. These factors are also the most suitable options for a statistical investigation because they are specified in standards.

Initially, the idea was to take electrode material as an independent factor, but the only welding equipment available was the MIG welder, which has a huge coil of feed wire. Using different feed wires would lead to the wastage of almost three-fourths of the coil. The Travel speed was selected based on the knowledge of the weld bead being deposited onto the workpiece.

Table 1. Factors and Levels

FACTORS	LEVELS	
	LOW (1)	HIGH (2)
Wire Speed	40 IPM	60 IPM
Voltage Setting	3	5
Travel Speed	9 IPM	18 IPM

Wire Speed is the feed speed at which the copper-coated steel wire is fed out of the welding gun. It is measured in Inch Per Minute (IPM). Voltage refers to the welding voltage and is represented by levels. The actual levels of voltage are obtained from the Millermatic 200 Voltage Conversion Chart as given in their user manual. A HIGH setting of voltage for this experiment was used. Travel Speed refers to how fast the welding arc is moved relative to the workpiece. It is also measured in Inch Per Minute (IPM) (Table 1, Figure 5).



Selecting Wire, Gas and Control Settings*

To read settings:
First number is voltage. Second number is wire speed.
(–) Means not recommended.

Example: 2/40

What Material are You Welding?	Suggested Wire Types	Suggested Shielding Gases and Flow Rate	Wire Sizes (Diameter)	Select Voltage and Wire Speed Based on Thickness of Metal Being Welded								
				3/8" (9.5 mm)	1/4" (6.4 mm)	3/16" (4.8 mm)	1/8" (3.2 mm)	14 ga. (2.0 mm)	16 ga. (1.6 mm)	18 ga. (1.2 mm)	20 ga. (0.9 mm)	22 ga. (0.8 mm)
Steel	Solid (or hard) ER70S-6	100% CO_2, 25 cfh	0.023" (0.6mm)	—	6/90	5/80	4/60	4/55	3/45	3/40	2/22	2/20
			0.030" (0.8mm)	—	6/70	5/60	4/45	3/30	3/28	2/18	2/25	—
			0.035" (0.9mm)	6/55	5/48	4/38	4/36	3/25	3/22	2/12	—	—
		75% Ar/25% CO_2, 25 cfh (Ar/CO_2 produces less spatter - better overall appearance)	0.023" (0.6mm)	—	5/90	4/80	3/65	3/60	2/40	2/35	1/22	1/20
			0.030" (0.8mm)	5/70	4/60	3/52	3/50	2/34	2/32	2/28	1/18	1/18
			0.035" (0.9mm)	5/55	4/48	3/42	3/40	3/35	2/28	2/22	1/12	—
Steel – for outdoor, windy applications or when weld appearance is not critical.	Flux core E71T-11	No shielding gas required	0.030" (0.8mm)	4/65	4/62	3/55	2/42	2/40	1/20	—	—	—
			0.035" (0.9mm)	4/52	4/50	3/40	2/32	2/30	1/18	—	—	—
			0.045" (1.1mm)	4/32	4/30	3/25	2/20	—	—	—	—	—
Stainless steel	Stainless steel ER 308, ER 308L ER 308LSi	Tri-Mix, 35 cfh (90% He/7.5% Ar/2.5% CO_2)	0.023" (0.6mm)	7/95	6/90	5/85	5/80	4/75	4/70	3/52	3/52	3/50
			0.030" (0.8mm)	7/85	6/80	5/75	5/70	4/60	3/47	3/45	3/40	—
			0.035" (0.9mm)	7/70	6/65	5/60	4/50	3/40	3/37	3/35	—	—
Aluminum with Spoolmate™ 3035 spoolgun.	Aluminum 4043 ER	100% Ar, 25 cfh	0.030" (0.8mm)	—	6/80	5/75	4/70	3/55	—	—	—	—
			0.035" (0.9mm)	7/80	6/70	5/65	4/60	3/50	—	—	—	—

Figure 5. Voltage Chart for the MIG Welder Machine in the Lab

3.4 Experimental Procedure

Step 1: Four plates 4ft in length will be cut to the required dimensions using a Chop saw (Figure 6).

Step 2: A belt grinder will be used to grind the plates. The main purpose was to get rid of the chips and irregularities on the edges of the plates, that were formed during the cutting process.

Step 3: MIG Welding is performed on the plates using the required settings obtained from the run order.

Step 4: Plates are allowed to cool at room temperature.

Step 5: Tensile testing is done on the MTS Machine.

Step 6: The axial force observations are then recorded from the MTS Test Suite Software. The unit of axial force is *kip*, which stands for Kilopounds. 1 Kip is equal to 1000 pounds.

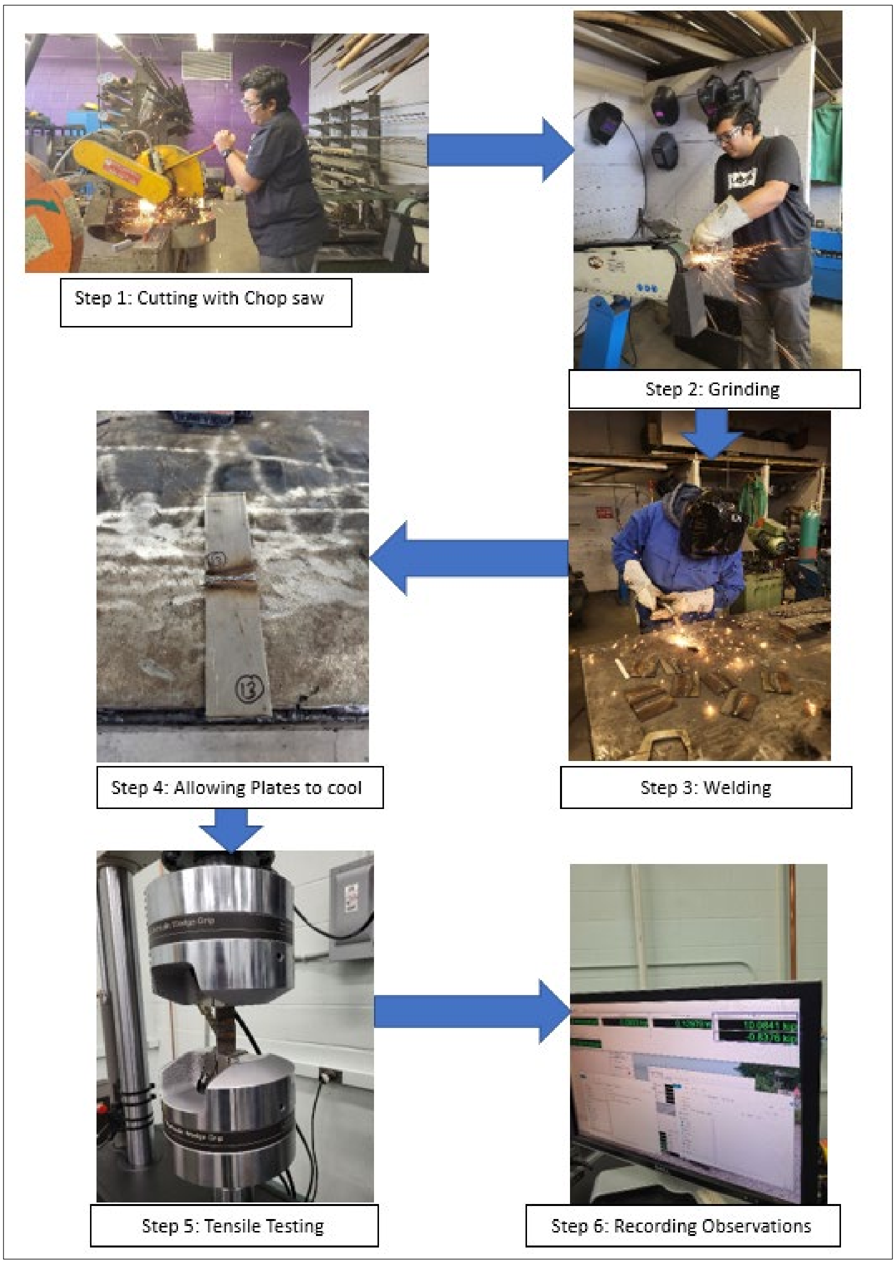


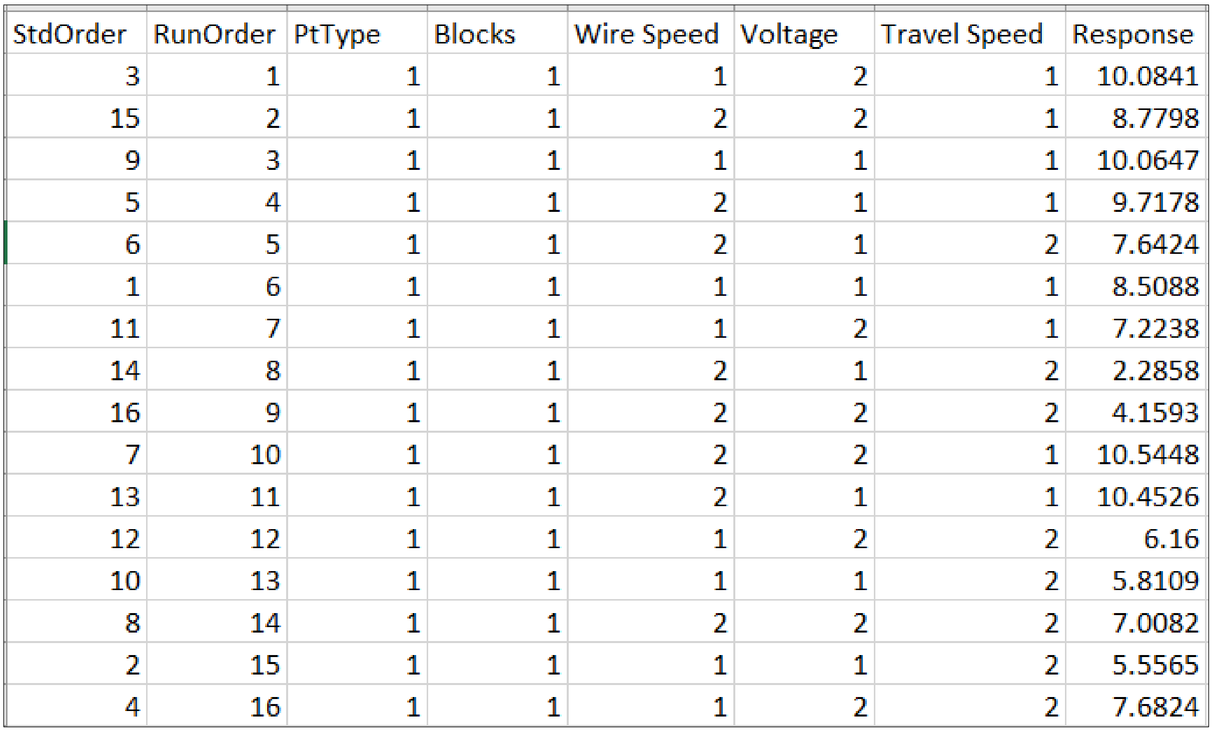
Figure 6. Experiment with pictures highlighting the procedure used

4. Data Collection

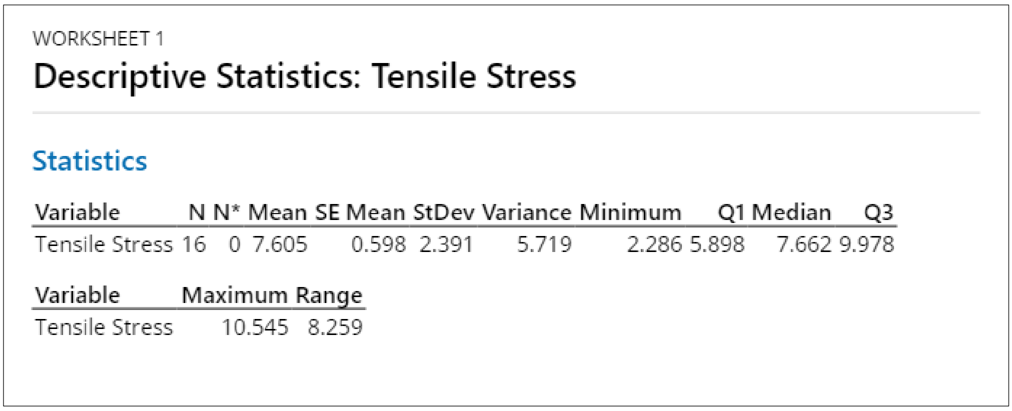
The experiment was conducted in the Engineering Projects Lab and the Material Testing Lab of Minnesota State University, Mankato, USA. The tensile test data was compiled from MTS Test Suite software that records each run being performed on the MTS tensile testing machine.

The design matrix is presented (Table 2), which comprises two replications with eight runs each.

Table 2. Design Matrix



StdOrder	RunOrder	PtType	Blocks	Wire Speed	Voltage	Travel Speed	Response
3	1	1	1	1	2	1	10.0841
15	2	1	1	2	2	1	8.7798
9	3	1	1	1	1	1	10.0647
5	4	1	1	2	1	1	9.7178
6	5	1	1	2	1	2	7.6424
1	6	1	1	1	1	1	8.5088
11	7	1	1	1	2	1	7.2238
14	8	1	1	2	1	2	2.2858
16	9	1	1	2	2	2	4.1593
7	10	1	1	2	2	1	10.5448
13	11	1	1	2	1	1	10.4526
12	12	1	1	1	2	2	6.16
10	13	1	1	1	1	2	5.8109
8	14	1	1	2	2	2	7.0082
2	15	1	1	1	1	2	5.5565
4	16	1	1	1	2	2	7.6824



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WORKSHEET 1
Descriptive Statistics: Tensile Stress

Statistics

Variable        N N* Mean SE Mean StDev Variance Minimum    Q1 Median    Q3
Tensile Stress 16  0  7.605   0.598  2.391    5.719      2.286 5.898   7.662 9.978

Variable        Maximum Range
Tensile Stress   10.545  8.259
```

Figure 7. Basic Statistical Data

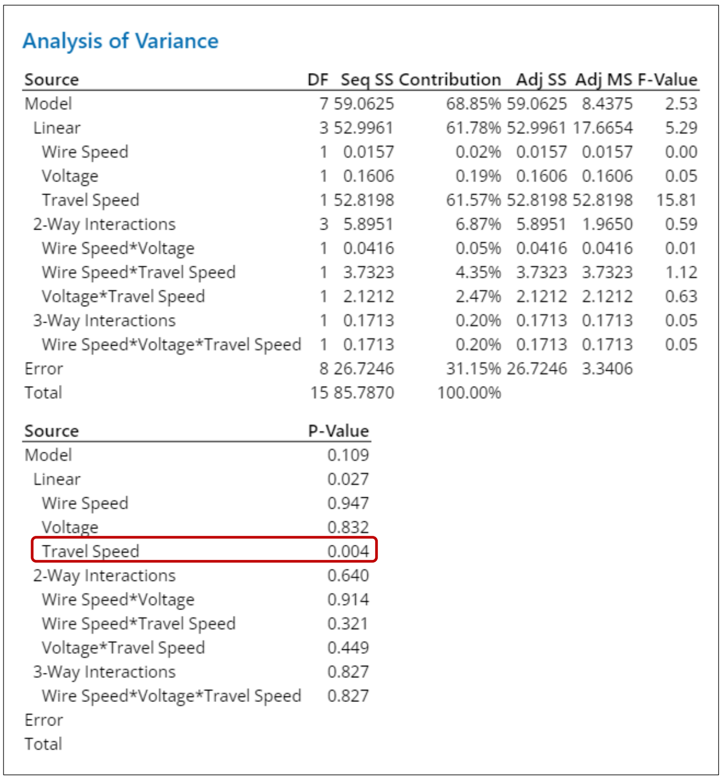
The descriptive statistics tool was run in Minitab and the following values were obtained. The mean is 7.605, the standard deviation is 2.391, and the median lies at 7.662. The upper and lower quartile range values were also obtained which are 9.978 and 5.898 respectively (Figure 7).

5. Results

5.1 Numerical Results

5.1.1 ANOVA (Analysis of Variance) Results

Table 3. ANOVA test



Analysis of Variance

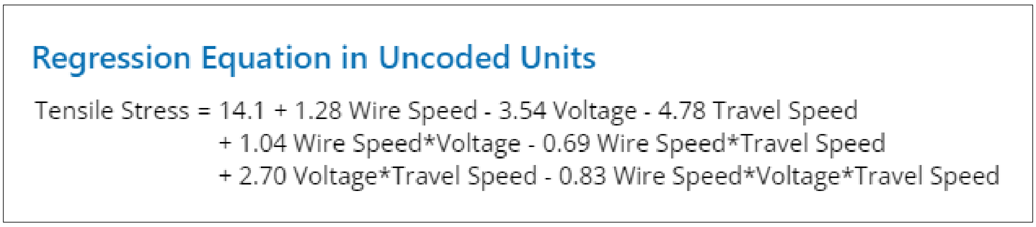
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Model	7	59.0625	68.85%	59.0625	8.4375	2.53
Linear	3	52.9961	61.78%	52.9961	17.6654	5.29
Wire Speed	1	0.0157	0.02%	0.0157	0.0157	0.00
Voltage	1	0.1606	0.19%	0.1606	0.1606	0.05
Travel Speed	1	52.8198	61.57%	52.8198	52.8198	15.81
2-Way Interactions	3	5.8951	6.87%	5.8951	1.9650	0.59
Wire Speed*Voltage	1	0.0416	0.05%	0.0416	0.0416	0.01
Wire Speed*Travel Speed	1	3.7323	4.35%	3.7323	3.7323	1.12
Voltage*Travel Speed	1	2.1212	2.47%	2.1212	2.1212	0.63
3-Way Interactions	1	0.1713	0.20%	0.1713	0.1713	0.05
Wire Speed*Voltage*Travel Speed	1	0.1713	0.20%	0.1713	0.1713	0.05
Error	8	26.7246	31.15%	26.7246	3.3406	
Total	15	85.7870	100.00%			

Source	P-Value
Model	0.109
Linear	0.027
Wire Speed	0.947
Voltage	0.832
Travel Speed	0.004
2-Way Interactions	0.640
Wire Speed*Voltage	0.914
Wire Speed*Travel Speed	0.321
Voltage*Travel Speed	0.449
3-Way Interactions	0.827
Wire Speed*Voltage*Travel Speed	0.827
Error	
Total	

For this experiment, the *null hypothesis* under consideration was that there are no significant factors that are affecting the response variable.

Since the ANOVA test shows (Table 3) the p-value of travel speed to be less than 0.05, it was found out to be the most significant variable, among others. This is because the other factors were found to have p values that were above 0.05, thereby failing to reject the null hypothesis.

5.1.2 Regression Model



Regression Equation in Uncoded Units

Tensile Stress = 14.1 + 1.28 Wire Speed - 3.54 Voltage - 4.78 Travel Speed
+ 1.04 Wire Speed*Voltage - 0.69 Wire Speed*Travel Speed
+ 2.70 Voltage*Travel Speed - 0.83 Wire Speed*Voltage*Travel Speed

(1)

As seen in equation (1), this regression equation is used to describe the relationship between the response and the factors used in the model (Heo et al., 2008). The equation in uncoded units signifies that we chose an option to standardize the continuous variables.

5.2 Graphical Results

5.2.1 Pareto Chart

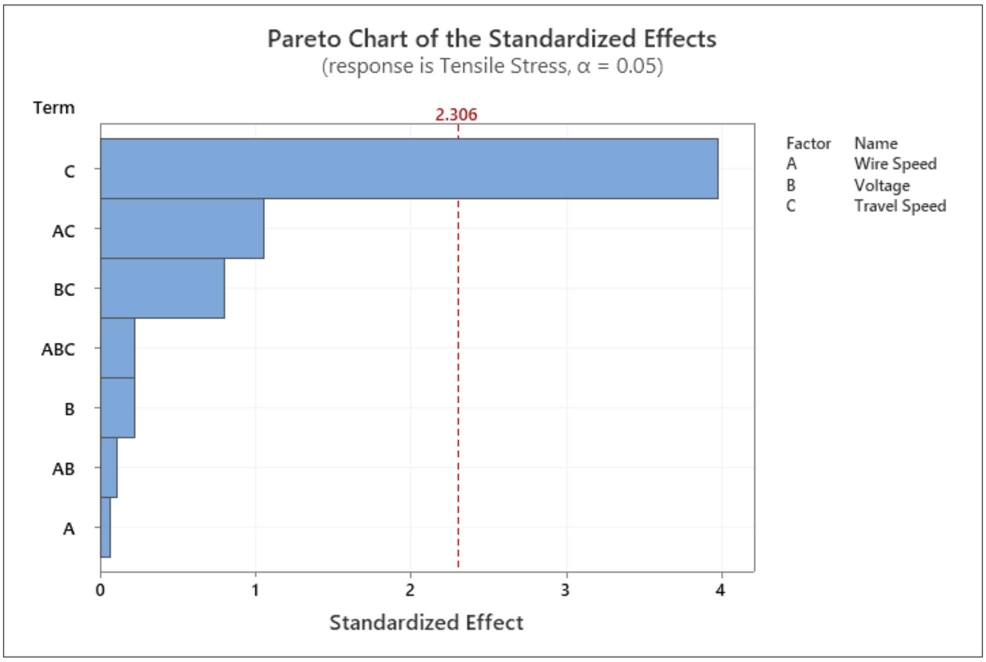


Figure 8. Pareto Chart

The Pareto chart (Figure 8) clearly identifies factor C as the most significant variable, which is the travel speed. It also shows the various interaction effects which have no major effect on the tensile stress but are still statistically relevant.

5.2.2 Normal Probability Plot

The normality plot (Figure 9) looks slightly concerning due to the presence of a few outliers. Hence, a normality test is performed for confirmation, namely the Anderson-Darling Test.

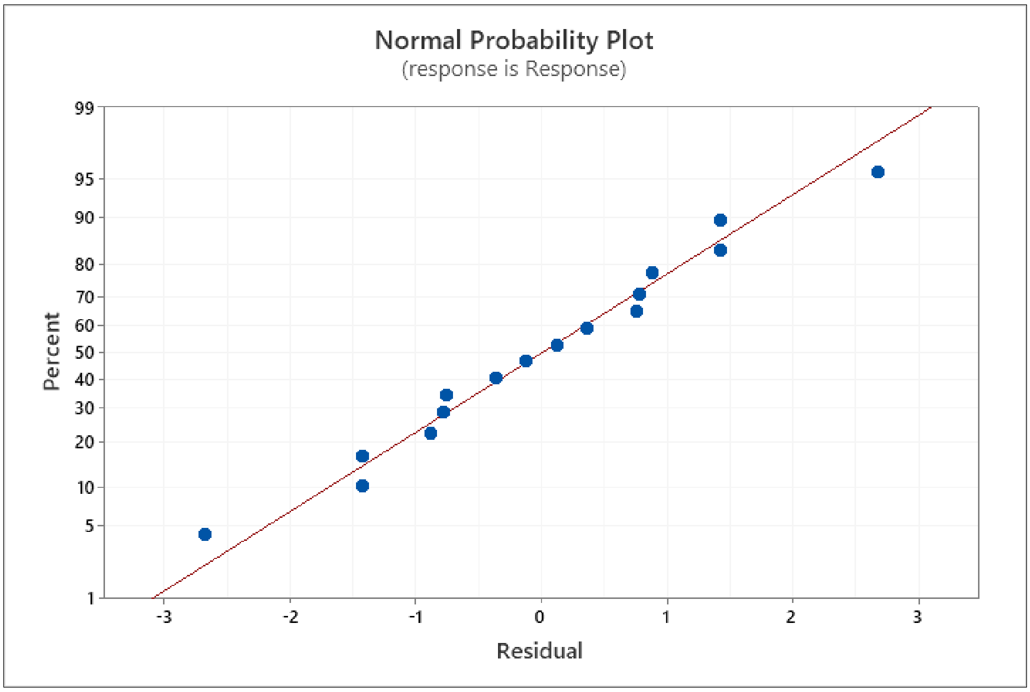
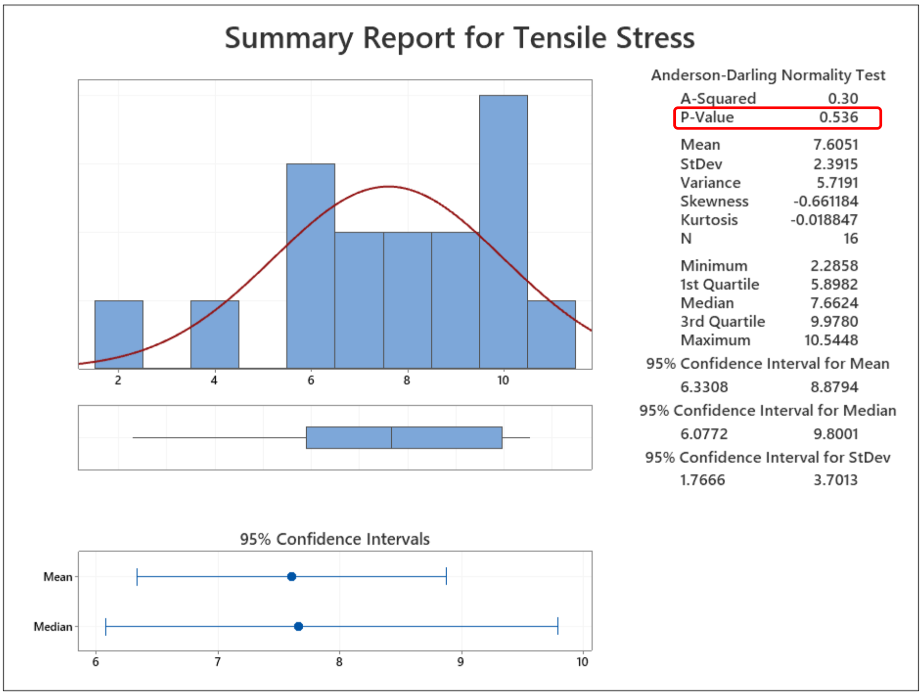


Figure 9. Normality Plot

The Anderson-Darling test for normality ensures that data conforms to the normal distribution and it follows a Gaussian curve, which is the primary assumption in the majority of statistical analyses (Nelson, 1998).

5.2.3 Anderson Darling Normality Test



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Anderson-Darling Normality Test
   A-Squared          0.30
   P-Value           0.536

   Mean             7.6051
   StDev            2.3915
   Variance         5.7191
   Skewness      -0.661184
   Kurtosis      -0.018847
   N                    16

   Minimum          2.2858
   1st Quartile     5.8982
   Median           7.6624
   3rd Quartile     9.9780
   Maximum         10.5448
95% Confidence Interval for Mean
   6.3308           8.8794
95% Confidence Interval for Median
   6.0772           9.8001
95% Confidence Interval for StDev
   1.7666           3.7013
```

Figure 10. Anderson Darling Normality Test

Figure 11. Residual versus Fits plot

Since the P value of the normality test (Figure 10) is greater than 0.05 (at 95% confidence interval), we fail to reject the null hypothesis and accept that the data is normally distributed.

5.2.4 Versus Fits and Order Plot

These graphs are useful in identifying patterns or discrepancies between the actual data points and the predicted data. This can give a clear picture of the model's accuracy and can highlight areas that need improvement.

The versus fits plot should be used to verify the assumption that the residual points have a constant variance, whereas the versus order plot is helpful to verify the assumption that the residuals are uncorrelated with each other Minitab 21.

The data points on the fits plot (Figure 11) are perfectly symmetrical, which confirms that there is no requirement for performing an equal variance test.

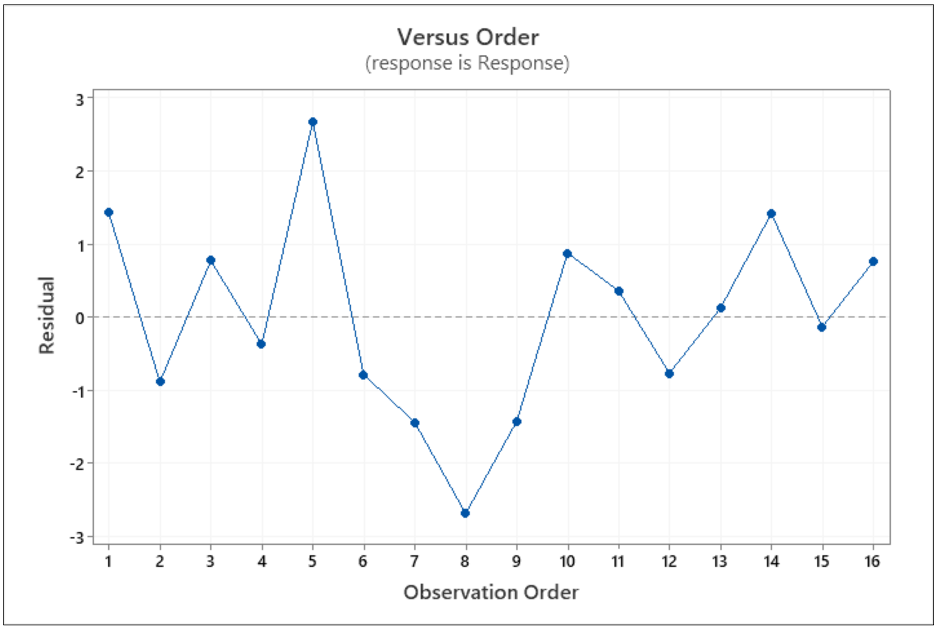


Figure 12. Residual versus Order Plot

The Versus Order plot (Figure 12) shows the randomness of the data points around the zero line, no visible patterns or trends, and a constant spread over time, which signifies that it is a well-fitted model.

5.2.5 Main Effects Plot

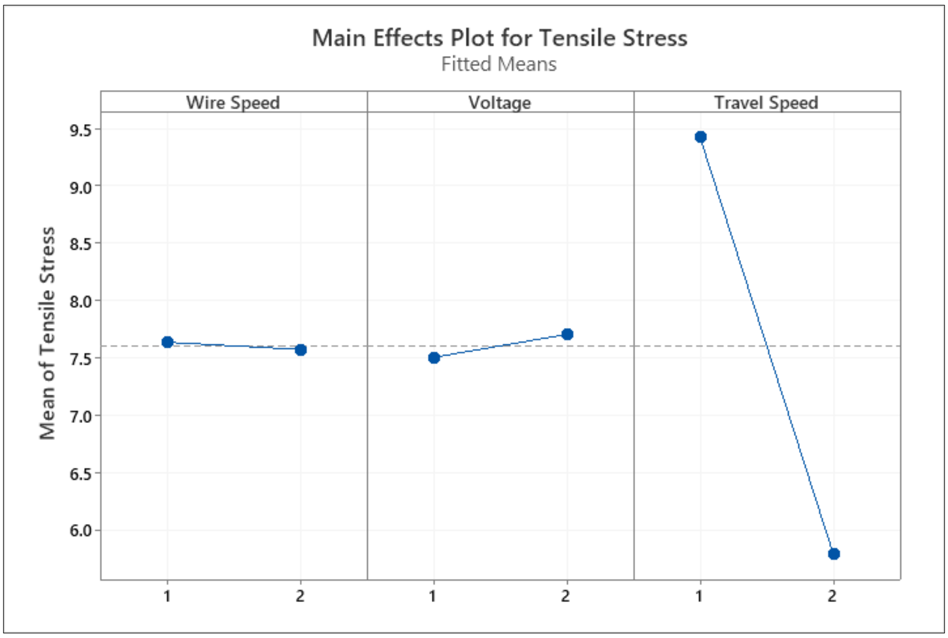


Figure 13. Main Effects Plot

The main effects plot (Figure 13) of factors A and B are linear, which means these factors have no significant effect and only C has a significant effect due to a slope.

5.2.6 Interaction Effects Plot

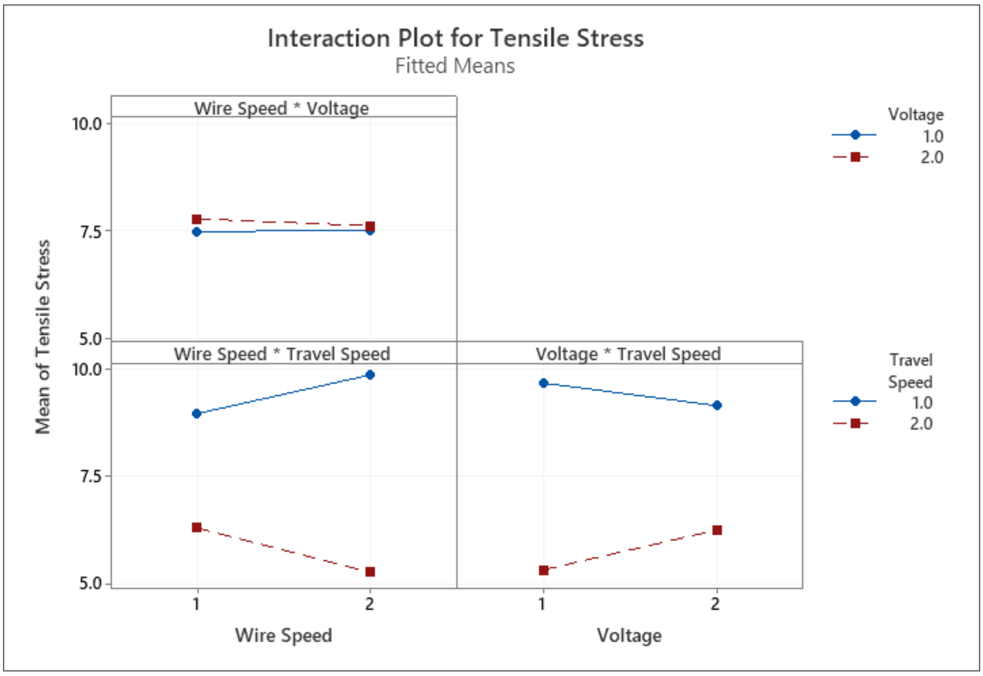


Figure 14. Interaction Effects Plot

The nature of lines in the interaction effect plot (Figure 14) provides information about their interaction effects. If the lines are parallel, there are no interaction effects between the factors. However, if the lines are nonparallel, an interaction occurs. The more nonparallel the lines are, the greater the strength of the interaction Minitab 21. This plot exhibits no intersecting lines amongst the factors which signifies that there are no major interaction effects in the experiment.

5.2.7 Cube Plot

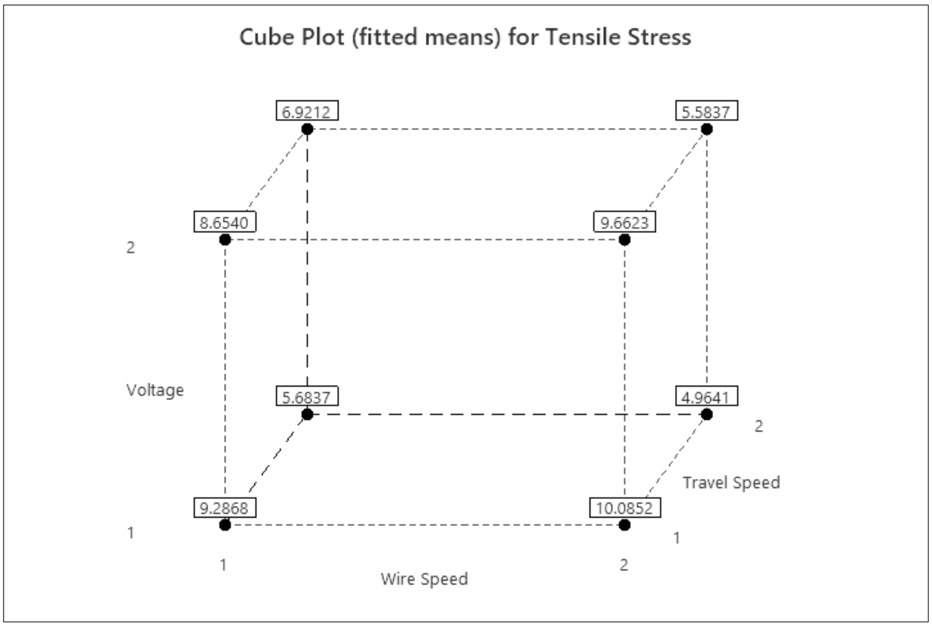


Figure 15. Cube Plot

The cube plot (Figure 15) shows the highest points at the corners and the average travel and wire speeds lie at the bottom plane of the cube.

5.2.8 Surface Plots

The surface plots are a part of the Response Surface Methodology (RSM). The main objective of this methodology is to determine the optimum operating conditions for the experiment and to identify a region that satisfies the target specifications (Ravikumar et al., 2005).

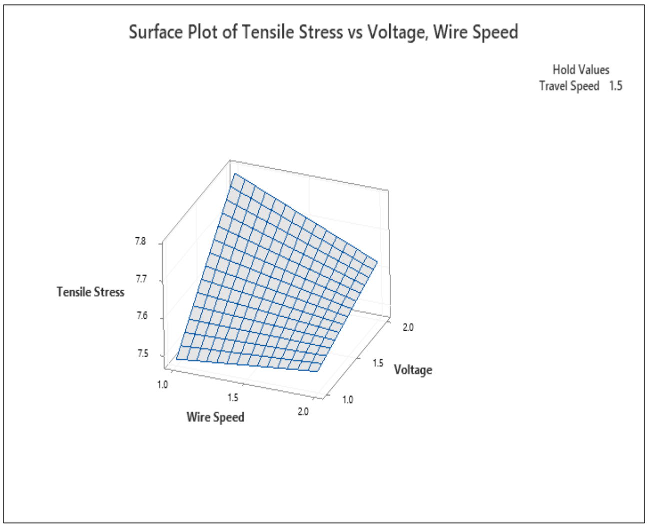


Figure 16. Surface Plot of Tensile Stress vs Voltage, Wire Speed

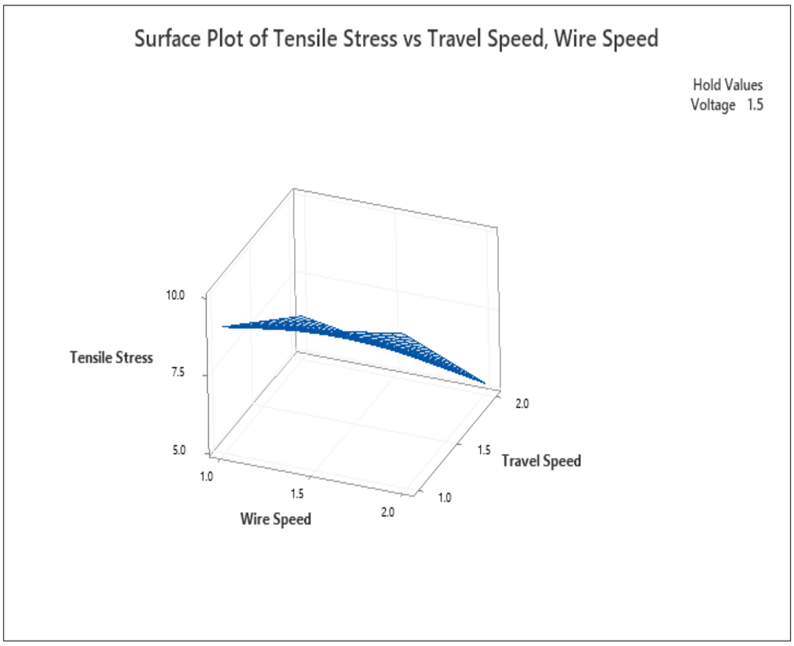


Figure 17. Surface Plot of Tensile Stress vs Travel Speed, Wire Speed

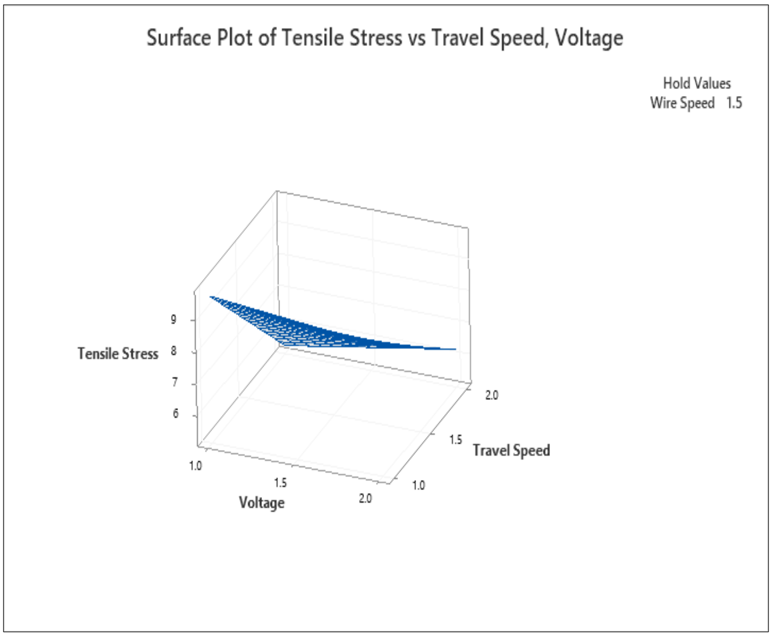


Figure 18. Surface Plot of Tensile Stress vs Travel Speed, Voltage

The plot in Figure 16 shows no curvature whereas the plots in Figures 17 and 18 show a slight curvature but are nonsignificant. The value of travel speed, voltage, and wire speed is held at 1.5 in the respective plots.

5.2.9 Contour Plot

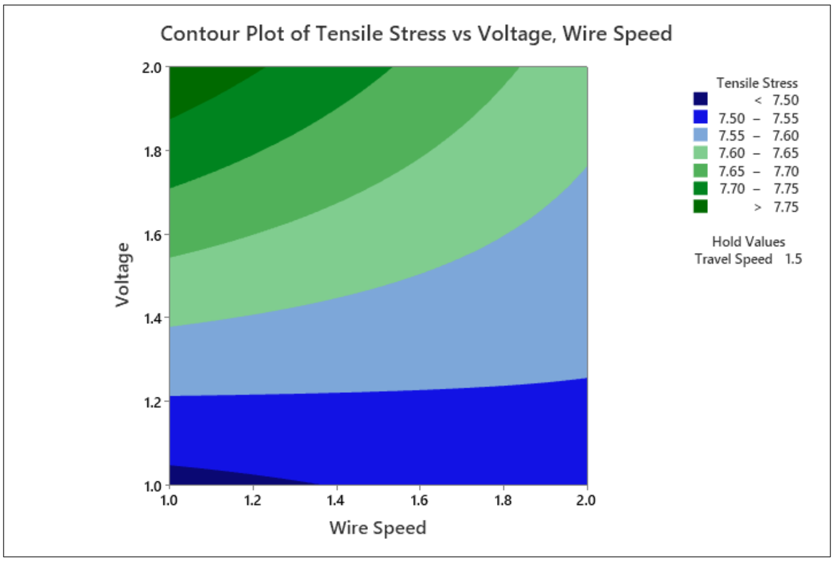
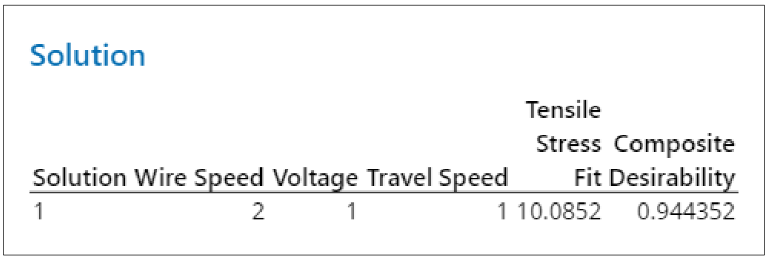


Figure 19. Contour Plot

From the contour plot (Figure 19), values lying in the dark green region would yield the highest tensile stress for the plates.

5.2.10 Response Optimizer



Solution

Solution	Wire Speed	Voltage	Travel Speed	Tensile Stress Fit	Composite Desirability
1	2	1	1	10.0852	0.944352

Figure 20. Response Optimizer Solution

The Response Optimizer in Minitab (Figure 20) yielded the ideal welding process parameters. The wire speed should be 40 inches per minute, the voltage setting should be at 3, and the travel speed should be maintained at 9 inches per minute.

6. Discussion

The analysis using statistical software validates the interdependence of these welding factors and the response variable, and further study using the response optimizer confirms the interaction between them. It was found that the only parameter with a significant influence on the tensile stress of the steel plates was the travel speed. As shown by Swami et al. (2018), the filler material tends to settle evenly while welding at slower rates and can positively affect the microstructure of the joints. This clearly asserts that to achieve a higher strength of the steel plates, one needs to weld at lower travel speeds.

In welding procedures, ensuring the quality and safety of manufactured products is of prime importance. Novice workers play a crucial role in this setting. Kobayashi et al. (2001) have highlighted the importance of specialist training for these individuals. Such training helps to maintain a safe working environment in addition to improving the skill sets of employees. These efforts guarantee the safety of people involved in the welding process as well as the quality of the final product by bridging the gap between theory and real-world application.

7. Conclusion

To summarize, this study has thoroughly examined various welding parameters through statistical analysis in order to determine how they affect the tensile strength of mild steel. The results reveal the intricate relationships between key variables and provide insightful information for improving welding procedures. The results of this study also support the ongoing improvement of welding techniques since it is important to maintain exceptional tensile strength in steel applications. Overall, this work provides a push toward improving the effectiveness and efficiency of steel welding procedures in a range of industrial settings.

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Biographies

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