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Optimized Stud Arc Welding Process Control Factors by Taguchi Experimental Design Technique

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Additional information is available at the end of the chapter

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1. Introduction

Welding is an ancient craft that combines art, science and human skill. It can be traced back to around 3000 BC, with the Sumerians and the Egyptians. The Sumerians used swords with parts joined by hard soldering. The Egyptians found that, after heating iron, it was much easier to work with welding just by hammering the parts to join them. Several objects that have been found in tombs and excavations, etc., indicate the exploitation of several welding techniques, such as “pressure” (hammering) welding, applied with several metal materials (gold, iron, bronze and copper, etc.) during those ancient times.

In the sixteenth century, the basic welding techniques were well known but not used to any great extent. In 1540, the Italian Engineer Vannoccio Biringuccio (as cited in Smith and Gnudi, 1990) explains in his book “The Pirotechnia”, published in Venice, that welding “seems to me an ingenious thing, little used, but of great usefulness”. During these middle ages, the art of blacksmithing was further developed and it was possible to produce any items of iron welded by hammering. The welding, as we know it today, was not invented until the nineteenth century.

A number of different processes can be used for joining studs to sheets or structure: resistance, friction and arc welding (stud arc welding or manual metal arc welding). Manual metal Arc Welding is sometimes used, but often only fillet welds are possible, and it is very slow. Stud Arc Welding (SAW) was invented just prior to World War II at the New York Navy Yard and developed for necessity to attach wood planking to naval aircraft carriers, and later it was used in the shipbuilding and construction industries. To undertake a weld, the welder first cleans the workpiece to bright shining metal. A stud is fitted with its ferrule into the chuck. The gun is pressed against the workpiece in the correct position and the

trigger squeezed. There are four steps of SAW process. First step the automatic solenoid of gun is energized, withdrawing the stud from the workpiece and starting the current to create an arc. The arc melts the end of the stud and the workpiece. When the preset time is complete, the current cut off. The spring in the gun plunges the stud into the molten pool to complete the weld. Once the weld is done, the welder removes the gun, breaks off the ferrule and inspects the weld. Figure (1) illustrates a stud arc welding process steps (Miller Welds Electrical Mng. Co., 2005).

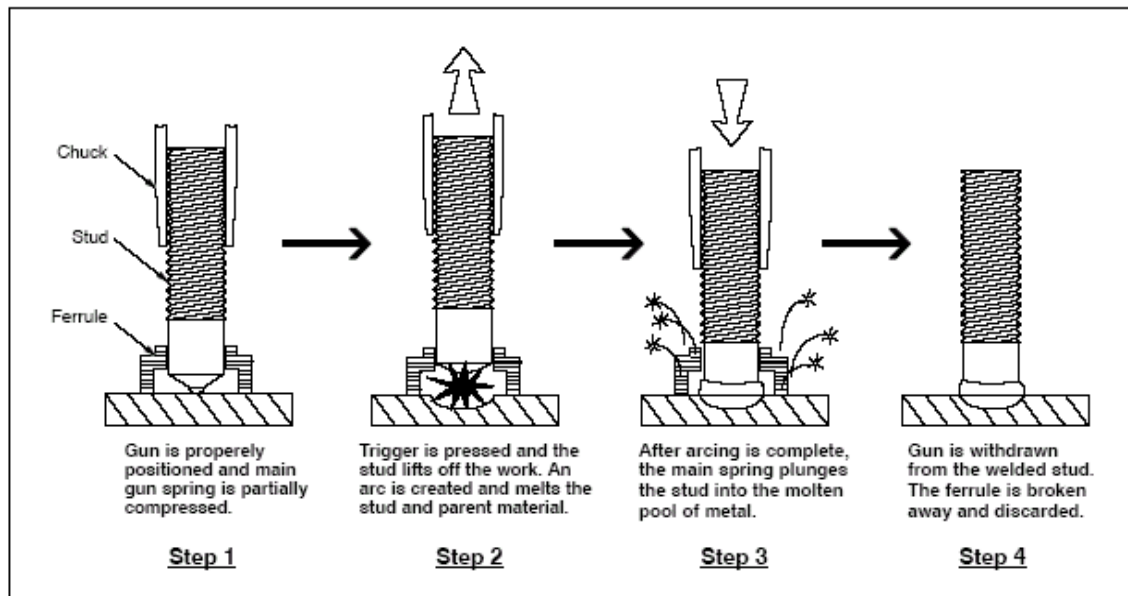


Figure 1. The stud welding process steps (Miller Welds Electrical Mng. Co., 2005).

The stud arc welding process includes the same electrical, mechanical and metallurgical principles as with other arc welding processes (Lee J. S. et al., 2009). The quality of the weld joint in the Drawn Arc Welding (DAW) process with a ceramic ferrule depends upon a number of factors such as: the type of the base metal and the stud material, the welding position, the welding time and other factors; however, the proper selection of welding parameters has an important role. The literature survey shows that, due to the short time of the welding cycle, simplicity in the use of equipment, cost efficiency and the application of the stud arc welding process are all well known in various manufacturing fields. Reviewing the previous literature surveys shows that the researchers have been concerned with the search for this process in two directions: the first direction is the examination of the process factors affecting mechanical properties - such as tensile stress weld or strain pieces - influenced by multiple factors, such as welding current, welding time, stud plunge and lift, and other factors - see reference (Klarić et al., 2009). References (Bursi O. S. & Gramola G., 1999) and (Lee et al., 2009) describe the ability of studs to develop full strength welds and discuss the fact that, in some cases, some welds were less than full strength. Reference (Anderson N. S. & Meinheit D. F., 2000) documents the embedment shear and tension tests of deformed bar anchors where no weld failures occurred and summarizes the results of extensive testing and studies from many sources in relation to the performance of the stud

welded anchor and other types of anchor devices. Reference (Hsu C. & Mumaw J., 2011) presents the findings of a weldability study of the drawn arc stud welding of various advanced high-strength steels (AHSS), including two grades of boron steel and one grade of dual-phase steel of various thicknesses, coatings from several automakers and benchmarked against mild steel. Researchers like (Strigel R. M., Pincheira J. A. & Oliva M. G., 2000) also consider examining failure in stud welding joints and they show that 19 % of samples examined fail - the weld's fail in the vicinity of the weld area. Eşme (2009) reports on an investigation of the effect and optimization of welding factors on the tensile shear strength in the Resistance Spot Welding (RSW) process. The experimental studies were conducted under varying electrode forces, welding currents, electrode diameters and welding times. The settings of the welding factors were determined by using the Taguchi experimental design method. The confirmation tests indicated that it is possible to increase tensile shear strength significantly by using the Taguchi method. The experimental results confirmed the validity of the Taguchi method for enhancing welding performance and optimizing the welding factors in the RSW process.

A second direction of research studies is the application of automated systems in the control procedure in relation to an interest in the research on the development of technology; the previous research indicates the evolution trend, especially since the procedure can be worked by automation, such as with robots - see (Samardžić I. & Klari Š., 2007), (Hsu et al., 2007) and (Hsu et al. 2008). In addition, the researchers studied the possibility of using neural network systems for optimization process parameters (Riyadh Mohammed Ali Hamza R. M. A., 2011).

In this chapter, an experimental study is conducted under varying welding times, sheet thicknesses, sheet coatings, welding currents, stud designs, stud materials, preheat sheets and surface conditions. The effectiveness of the welding factors levels on the joint and tensile strength is determined via Analysis of Variance (ANOVA). The optimum welding parameter combination is obtained using the analysis of the signal-to-noise (S/N) ratio and the quality loss function. The confirmation tests indicated that it is possible to increase the tensile strength significantly using the Taguchi method, by which 225 samples are tested.

Due to the mentioned importance of proper parameter selection, the main aim of this optimization technique is to ascertain the assumption that the specific selection of welding factors will influence weld tensile strength and that the proper selection of factors will give a weld joint the desired tensile strength.

2. Factors of the stud arc welding process

A process can be defined as a combination of inputs - such as materials, machines, manpower, measurements, environments and methods - that results at various outputs as the measurements of performance (Conti, Kondo & Watson, 2003). The inputs x_1, x_2, \dots, x_p are controllable factors, such as temperature, pressure, feed rates and other process variables. The inputs z_1, z_2, \dots, z_q are uncontrollable (or difficult to control) input factors, such as environmental factors or the properties of a raw materials provided by the supplier, as

shown in figure (2). The manufacturing process transforms these inputs into an output that has several quality characteristics (Schmidt & Launsby, 1992).

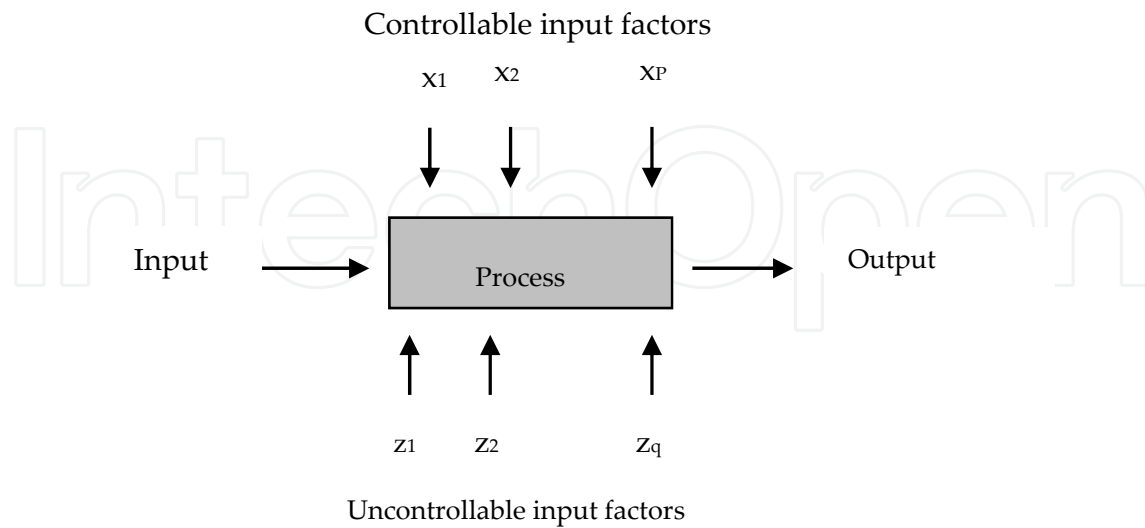


Figure 2. General model of a process (Schmidt & Launsby, 1992).

There are two types of arc-stud welding processes: Capacitor Discharge Welding and Arc Stud Welding.

2.1. Capacitor discharge welding

In this process, the Direct Current (DC) produced by the rapid discharge of stored electrical energy from a bank of capacitors is used to create an arc between a stud and the sheet or structure. Pressure is applied immediately following electrical discharge to form the weld and no flux or ferrule is required. The arc stud processes are quick and access to the other side of the joint is not required (as is necessary for bolted connections). Because of the short welding cycle, the HAZs are narrower than for other arc processes. (Samardžić I., 2007) explains that Capacitor Discharge Stud Welding (CD) can be accomplished by a specially-drawn arc stud welding process - known as the "short cycle" process - whereby stud welding to sheet metal is characterized by the use of a high current and a short time.

The stud is held in a gun. When the trigger is operated, the capacitor is discharged so as to fuse the end of the stud and the base material; then, the stud is plunged into the weld pool. Welds are produced using very high currents (6000A) for very short durations of about 3 to 15 milliseconds. Because of the percussive nature of the process, surface coatings are removed more effectively than with the arc stud process. Less similar combinations can be welded (e.g., brass to steel), than with the arc stud process because of the short duration. The process is also suitable for welding studs to thin sheets without damaging the surface coating on the opposite side.

The capacitor discharge method is limited to studs of 8 mm and less for economic reasons. It is less tolerant to rust and scale. Because of these limitations, this process is used less than with the arc stud welding process for heavy fabrication. The most common application of

capacitor discharge welding is to join the thermocouple to the steel structure for monitoring preheat and post-weld heat treatment. The scar that remains after the removal of the thermocouples is insignificant (Taylor, 2001).

2.2. The arc stud welding process

During this process, an arc is established between the stud and the workpiece using a conventional welding power source. After a brief time, the stud is plugged into the weld pool and the current is shut off. The process is quick and there is little time for detrimental phases to form. The main limitation is that it is intolerant to contamination and the surface to be welded should be free of rust, scale, paint and other contaminants.

The welding factors (the current and arc time) depend upon the material type and the size of the stud base. The current used is between 250 and 600 Amperes and the cycle time is 0.13 seconds to 1 second for studs of a diameter of 3 mm to 22 mm. An average of around six studs can be welded per minute.

2.3. The required process equipment

The most basic equipment is a stud gun connected to a control unit that is connected to a source of DC power. Some modern stud welding equipment includes the controller and the power source as one unit, but it is possible to obtain a controller and a gun utilizing an existing DC welding power source. Figure (3) illustrates that the process equipment consists of a stud gun, a control unit for timing the weld, a DC power source and a suitable weld cable.

The stud gun consists of the following components (Taylor, 2001):

- A spring-load chuck for holding the stud.
- An adjustable spacer for holding the stud gun against the workpiece.
- A solenoid coil to lift the stud away from the workpiece by a preset distance of approximately 3 mm.
- A trigger for initiating the welding cycles.

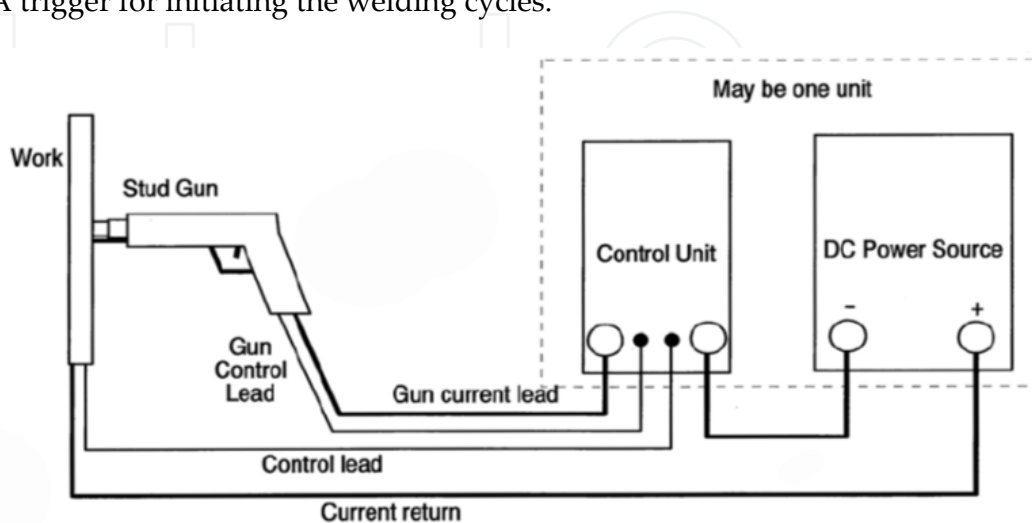


Figure 3. Arc Stud Welding Equipment (Taylor, 2001).

Most welding is undertaken using a hand-held gun. An automatic stud gun - which is fixed to robot arm or another fixture - can be used to automate the process. The controller has a solenoid switch to turn the current on and off rapidly as well as timers to control the automatic welding cycle and the adjustment of the current and the cycle time.

2.3.1. Studs and ferrules

Studs can have circular, square or rectangular bases. If the base is rectangular, the width should not be more than five times the thickness. It must have a shape that is capable of being held in the chuck; otherwise, the form of the stud is limitless. The most common stud types are screw fasteners and shear studs, but hooks, rings, rings, brackets and many other items can be made. Studs are available in a variety of materials. Carbon steel studs are semi-killed or fully-killed carbon steel of grades 1010 to 1020 in the cold drawn condition (Taylor, 2001).

The studs for most materials have a flux tip. They have to be supplied by a reputable stud-welding supplier, who is required by code to perform qualification tests. Those from other than reputable suppliers risk not producing satisfactory welds. Studs and ferrules should be from the same supplier.

Each stud is supplied with a matching ceramic ferrule so as to:

- Protect the arc by restricting air flow.
- Concentrate the arc heat to the weld area.
- Mould the weld flash.
- Prevent the charring of adjacent materials.

The ferrule is broken off when the weld is complete.

2.4. Application of the stud arc welding process

The stud arc welding process is applied in different production areas, such as boiler production, the motor vehicle industry, bridge construction and shipbuilding, due to the efficiency of the process.

The application of draw arc welding with a ceramic ferrule plays an important role in steam boiler production. This process is successfully used in ship building and the automobile industry, etc. The stud welding process is used for fixing in place the cryogenic insulation of membrane tanks in ship building (Lee et al., 2009). In addition, stud welding is widely used in the construction industries and in bridge construction in particular (composite steel/concrete structures). There are many different stud welded products that are commonly used in the manufacture of precast/pre-stress components, including threaded, headed and deformed bars (Bursi & Gramola, 1999).

2.5. Stud welding failures

The stud butt fully welds with the base material such that there is no unfused central area that is a feature of fillet welded attachments. Because the weld is a full penetration, the small

amount of flash interference is much less with an attachment than with a fillet weld would. For the full strength of the stud, the base metal thickness should be at least 1/3 of the stud base diameter. Studs can be closer to a flange edge than with threaded connections. The basis for loading is the smallest cross section of the stud (Taylor, 2001).

When the proper operation of stud welding equipment is combined with good quality control and inspection procedures, full strength welds can be obtained consistently and can result in the optimal performance of the studs. However, improper stud welding process factors cause stud failures. The root causes for weld or stud failures can usually be attributed to one or more of the following factors (Chambers, 2001):

- Unacceptable base plate materials or plate surface conditions.
- Inappropriate weld settings.
- Malfunctioning or obsolete equipment.
- Little or no formal training for stud welding operators.
- A lack of quality control and inspection procedures.

3. The Taguchi experimental design methodology

Experimental design is a subject with a set of techniques and body of knowledge which assists investigators in conducting experiments by better analysing the results of experiments and finding the optimal factor combinations to achieve the intended objectives – see (Montgomery D.C., 2009) and (Antony J. & Kaye M., 1999). Stud arc welding technology has generally continued to grow vigorously because of new applications. Tensile strength quality is one of the key factors in achieving good welding process performance and so the purpose of this study is to improve the tensile strength of stud joints by using the Taguchi Experimental Design Technique. In the following sections, some of the most important concepts in the design of the experimental technique will be explained.

3.1. Measure of variation (measure of dispersion)

This describes how the data is spread out or scattered on each side of the central value (mean). The elements involved in the measurement of variation are explained in two sections below.

3.1.1. The range of data

For a series of numbers, the range is the difference between the largest and the smallest values of observation. The range equation is:

$$r = x_h - x_l \quad (1)$$

Where

- r = range
- x_h = highest observation in a data

- x_i = lowest observation in a data

3.1.2. Standard deviation

Which of a set of (n) numbers x_1, x_2, \dots, x_n denoted by (S) and defined by:

$$S = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1}} \quad (2)$$

where (S) is the root mean square of the deviations of each number x_i from the mean \bar{x} .

3.2. Target value

In the data analysis, the target value - or an objective value - is a parametric quantity identified as the standard against which all measurements or calculations of the same response are to be evaluated. The target value is represented by T (Buyske S. & Trout R., 2003).

3.3. Sum of Squares (SS)

The sum of squares (SS) of a factor i at level k was calculated according to the equation (Buyske S. & Trout R., 2003):

$$SS_i = \sum_K \frac{\left(\sum_J Y_j \right)^2}{N_K} - \frac{\left(\sum_J Y_J \right)^2}{N} \quad (3)$$

where N is the total number of experiments, N_k is the number of levels and Y_j is the mean response. The total sum of squares (SS_T) is calculated using equation:

$$SS_T = \sum_J Y_J^2 - \frac{\left(\sum_J Y_J \right)^2}{N} \quad (4)$$

Experimental error (S_e) is calculated from:

$$S_e = SS_T - \sum SS_i \quad (5)$$

3.4. Degree of freedom

The degree of freedom, as an integer associated with a statistic, is the number of available independent squares of the associated statistic. If the independent sum of the squares is n , then the number of degrees of freedom denoted by f is equal to $n-1$.

3.5. Variance

The variance is defined as the sum of the squares of the deviations of the observation data from a specific value, divided by the degrees of freedom f . The variance - sometimes called the mean square - is denoted by V (Steiner S. H. & MacKay R. J., 2005).

$$V_i = \frac{SS_i}{f_i} \quad (6)$$

3.5.1. Analysis of variance

The relative magnitude of the effect of different factors can be obtained by the decomposition of the variance, namely ANOVA - this is given in table (1). The experimental design permits the effects of numerous factors to be investigated at the same time. When many different factors dynamically affect a given quality characteristic, ANOVA is a systematic and meaningful way of statistically evaluating experimental results (Montgomery D. C., 2009).

Sources of variation	Degrees of freedom F	Sum of squares SS	Mean square V	Pure sum of squares \acute{S}	F-ratio	Percent contribution (%)
Factor(a)	1	s_a	v_a	\acute{s}_a	F_a	\acute{a}
Error(e)	$n-1$	s_e	v_e	\acute{s}_e	1	\acute{e}
Total(t)	N	s_t		\acute{s}_t		100.0

Table 1. ANOVA table

Where:

1. Variance ratio

$$F_a = \frac{v_a}{v_e} \quad (7)$$

2. Sum of squares

$$s'_a = s_a - (f_a \times v_e) \quad (8)$$

$$s'_e = s_e + (f_a \times v_e) \quad (9)$$

3. %age contribution:

$$a' = \left(\frac{s'_a}{s_t} \right) \times 100 \quad (10)$$

$$e' = \left(\frac{s'_e}{s_t} \right) \times 100 \quad (11)$$

After n pieces of experimental data are collected and after the values of \acute{a} and \acute{e} are calculated, significant testing provides the criterion for making such decisions. The F-tests are used to statistically determine whether the constituents - the total sum of squares which are decomposed - are significant with respect to the components that remain in the error variance. The specific numerical confidence levels, depending upon which F-table is used, are called the level of significance. When the variance ratios F_a are larger than the F-table at the 5% level, then the effect is called significant at the 5% level (Montgomery D.C., 2009).

3.6. The Larger-the-better Signal to Noise (S/N) ratio

A signal-to-noise (S/N) ratio is a measure of performance which estimates the effect of the noise factors on the quality characteristic (Taguchi G., Chowdhury S., & Wu Y., 2005; Ross, P. J., 1986). The S/N is defined as:

$$\frac{S}{N}_{LTB} = -10 \log \left(\frac{\sum \frac{1}{y_i^2}}{n} \right) \quad (12)$$

where y = response, n = run experiment number.

3.7. The Taguchi Losses Function

The Taguchi quality losses' function for the larger-the-better is (Taguchi G., Chowdhury S. & Wu Y., 2005; Ross, P. J., 1986):

$$L(y) = A_o \Delta_o^2 \frac{1}{y^2} \quad (13)$$

A_o is the loss (stated in monetary or scaled monetary units) at a specified distance, Δ_o , from the target, T , and y is the performance measure.

3.8. The Orthogonal Array (OA)

Orthogonal Arrays (OA) are a special set of Latin squares, constructed by Taguchi in order to lay out the product design experiments. For each OA, a code is available in the form of L_{ab^c} , where (a) is the number of experiments, (b) is the number of levels for each factor and (c) is the number of columns in the array (Taguchi G., Chowdhury S. & Wu Y., 2005; Ross P. J., 1986).

4. Experimental work

The Taguchi experimental design is a statistical technique that allows the running of the minimum number of experiments to optimize the process.

4.1. (The DABOTEK stud welding) machine

The experimental work was executed using the DABOTEK stud welding device. The welding current can be set at five grades, such as (350, 540, 750, 900 and 1250 Amperes). The welding time can be set at grades of 0.05 seconds (from 0.05 seconds to 1 second). The machine that was used in the experiments is shown in figure (4).



Figure 4. The DABOTEK stud welding machine

4.2. The identification of process factors

Problem identification is critical for any industrial experiment, since the experimental and analysis stages are based on this. One of the most frequently used methods for identifying the problem is brainstorming. Brainstorming is an activity that promotes team participation, encourages creative thinking and generates various ideas over a short period of time. For an investigation into the possible causes of undesirable variability in the stud welding process, the researcher modified a cause and effect diagram that lists several suspected causes of this variability. Figure (5) illustrates the cause and effect of the problem under study. The researcher used brainstorming in conjunction with Cause and Effect Analysis (CEA) to identify the control factors which are to be considered for the experiment.

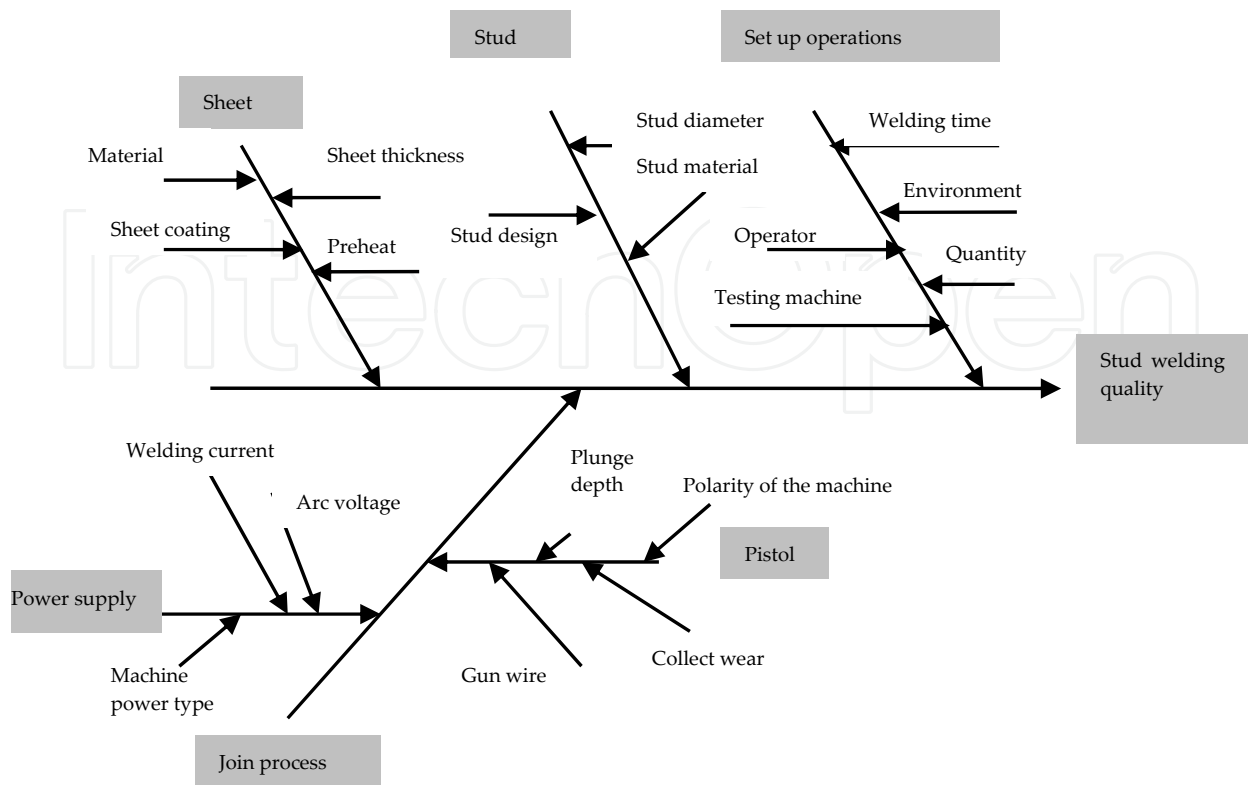


Figure 5. The suggested stud welding cause and effect diagram

Figure (5) shows that many factors play an important role in the stud welding process; they are separated into five main groups:

1. The sheet group

The factors that can be distinguished for these groups are:

- Sheet material.
- Sheet thickness.
- Sheet coating.
- Sheet preheating.

2. The stud group

The factors that can be distinguished for this group are:

- Stud design.
- Stud material.
- Stud diameters.

3. The welding machine group

The factors that can be distinguished for this group are:

- The power supply properties (voltage, current, machine power type (Continuous Electric Arc or Direct Capacitor Arc)).

- The pistol properties (gun wear (new or used), the polarity of machine and the gun wire length).

4. The setup welding operations group

The factors that can be distinguished for this group are:

- The welding time adjustment.
- The quantity of the studs to be welded.
- The operator performance.
- The environment.

5. The arc machine pistol group

The factors that can be distinguished for this group are:

- The polarity of the machine.
- The plunge depth.
- The gun wire.
- The collect wear.

To implement the experimental welds samples, eight independent control factors were chosen to improve the stud welding process. These factors are: welding time, sheet thickness, sheet material, welding current, stud design, stud material, preheat sheet and surface cleaning.

4.3. Selection of the factor levels and the range of factor settings

The selection of a number of levels depends upon how the outcome (tensile strength) is affected due to the different level settings. The levels for control factors are shown in table (2).

		Sheet material (C)																
		K52355								K14358								
Thickness mm	Process factor	unit	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
1.6	(A)	Welding time (second)	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
	(D)	Welding current (Ampere)	350	540								350	540					

Sheet material (C)		K14358				K52355				unit
Level 8										
Level 7										
Level 6										
Level 5										
Level 4										
Level 3										
Level 2	Flange stud	40CrMnMo S8-6	No preheating	Clean sheet	0.2	540	Flange stud	40CrMnMoS8-6	No preheating	Clean sheet
Level 1	Small stud	54NiCrMoS6	Preheating	Oil sheet	0.15	350	Small stud	54NiCrMoS6	Preheating	Oil sheet
Level 8					0.5					
Level 7					0.45					
Level 6					0.4					
Level 5					0.35					
Level 4					0.3					
Level 3					0.25					
Level 2	Flange stud	40CrMnMo S8-6	No preheating	Clean sheet	0.2	540	Flange stud	40CrMnMoS8-6	No preheating	Clean sheet
Level 1	Small stud	54NiCrMoS6	Preheating	Oil sheet	0.15	350	Small stud	54NiCrMoS6	Preheating	Oil sheet
Process factor	Stud design	Stud material	Preheating	Surface cleaning	Welding time	Welding current	Stud design	Stud material	Preheating	Surface cleaning
symbol	(E)	(F)	(G)	(H)	(A)	(D)	(E)	(F)	(G)	(H)
Thickness mm					3.175					

Table 2. The Levels of the welding time control factors for the experiments.

4.4. Method of measurement

The researcher took a sample containing ten pieces for stud welding depending upon the value for the welding time and the current in order to define the variety of the tensile strength of the samples. The results are in table (3). The dot plot for the data is shown in figure (6). The mean is 330.53 N/mm², the standard division is 57.560 N/mm² and the range is 189.90 N/mm².

Piece Number	1	2	3	4	5	6	7	8	9	10
Tensile Strength (N/mm ²)	310.5	377.8	352.1	243.1	350.3	342.4	253.8	354.6	432.4	289.7

Table 3. The tensile strength of the samples before the experiments

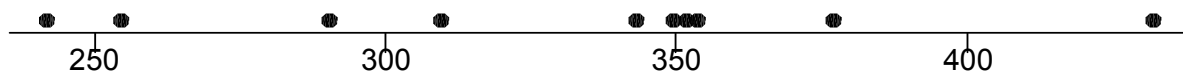


Figure 6. The dotplot for the observed data.

4.5. The Orthogonal Array (OA) design

The number of degrees of freedom required for the experiment must be greater than 14 (7+7). A Taguchi L₁₆2⁷1⁸ orthogonal array (OA) design, with seven in two levels and one in eight levels is shown by table (4) for the code design matrix.

Run	Welding time	Sheet thickness	Sheet material	Welding current	Stud design	Stud material	Preheat	Surface cleaning
1	1	1	1	1	1	1	1	1
2	1	2	2	2	2	2	2	2
3	2	1	1	1	1	2	2	2
4	2	2	2	2	2	1	1	1
5	3	1	1	2	2	1	1	2
6	3	2	2	1	1	2	2	1
7	4	1	1	2	2	2	2	1
8	4	2	2	1	1	1	1	2
9	5	1	2	1	2	1	2	1
10	5	2	1	2	1	2	1	2
11	6	1	2	1	2	2	1	2
12	6	2	1	2	1	1	2	1
13	7	1	2	2	1	1	2	2
14	7	2	1	1	2	2	1	1
15	8	1	2	2	1	2	1	1
16	8	2	1	1	2	1	2	2

Table 4. Code design matrix orthogonal array L₁₆2⁷1⁸.

4.6. Experimental preparation and the process run

In this step, the main task was to construct the uncoded design matrix for the experiment. The uncoded design matrix is shown by table (5).

Run	Welding time	Sheet thickness	Sheet material	Welding current	Stud design	Stud material	Preheat	Surface cleaning
1	0.15	1.6	K14358	350	Small	54NiCrMoS6	Preheat	Clean sheet
2	0.15	3.175	K52355	540	Large	40CrMnMoS8-6	No Preheat	Oil sheet
3	0.2	1.6	K14358	350	Small	40CrMnMoS8-6	No Preheat	Oil sheet
4	0.2	3.175	K52355	540	Large	54NiCrMoS6	Preheat	Clean sheet
5	0.25	1.6	K14358	540	Large	54NiCrMoS6	Preheat	Oil sheet
6	0.25	3.175	K52355	350	Small	40CrMnMoS8-6	No Preheat	Clean sheet
7	0.3	1.6	K14358	540	Large	40CrMnMoS8-6	No Preheat	Clean sheet
8	0.3	3.175	K52355	350	Small	54NiCrMoS6	Preheat	Oil sheet
9	0.35	1.6	K52355	350	Large	54NiCrMoS6	No Preheat	Clean sheet
10	0.35	3.175	K14358	540	Small	40CrMnMoS8-6	Preheat	Oil sheet
11	0.4	1.6	K52355	350	Large	40CrMnMoS8-6	Preheat	Oil sheet
12	0.4	3.175	K14358	540	Small	54NiCrMoS6	No Preheat	Clean sheet
13	0.45	1.6	K52355	540	Small	54NiCrMoS6	No Preheat	Oil sheet
14	0.45	3.175	K14358	350	Large	40CrMnMoS8-6	Preheat	Clean sheet
15	0.5	1.6	K52355	540	Small	40CrMnMoS8-6	Preheat	Clean sheet
16	0.5	3.175	K14358	350	Large	54NiCrMoS6	No Preheat	Oil sheet

Table 5. Uncoded design matrix array $L_{16}2^7$ ⁸

Run	Actual run order	Tensile strength (N/mm ²)						Mean N/mm ²	Standard deviation N/mm ²
1	5	175.73	213.23	143.66	195.09	210.50	155.60	182.302	28.860
2	9	288.70	251.20	330.40	284.99	225.90	300.70	280.315	36.946
3	13	284.39	198.56	225.89	245.87	276.24	263.54	249.082	32.539
4	3	359.99	420.50	428.42	300.03	387.38	367.54	377.310	46.790
5	12	190.70	245.87	235.90	298.46	164.33	289.46	237.453	52.977
6	11	370.45	392.68	191.74	360.38	288.70	383.26	331.202	77.637
7	8	321.60	139.00	349.05	310.00	362.93	457.50	323.375	104.318
8	1	331.96	326.32	331.15	401.60	387.26	314.78	348.828	36.095
9	4	388.10	233.60	372.20	287.95	225.43	278.00	297.547	68.611
10	2	530.00	460.72	549.85	375.12	410.53	375.89	450.352	76.343
11	15	305.40	383.20	456.00	378.00	478.00	375.00	395.933	62.388
12	7	152.09	160.74	170.76	166.80	250.88	132.45	172.287	40.835
13	16	219.19	152.97	250.85	257.16	266.78	198.75	224.283	43.258
14	10	155.65	180.45	289.40	220.68	225.35	248.78	220.052	47.705
15	14	289.36	215.62	318.43	256.84	288.23	145.63	252.352	62.900
16	6	185.32	178.45	223.21	155.82	298.33	188.43	204.927	50.651

Table 6. Tensile strength of the samples.

5. Results, analysis and discussions

The results of the experiments conducted depend upon the $L_{16}2^{718}$ OA with randomized order, as shown in table (6).

5.1. Determination of the optimum condition for the process

One objective is to reduce the variability in the tensile strength and to bring the mean as close as possible to the target. The target is 728.48 N/mm², which is the tensile strength of the stud. The optimization procedure by Taguchi for the study is:

Stage (1): Calculate the SNR for each experimental design point. The SNR for the larger-the-best quality characteristic is calculated by equation (12). Substitute the values into the above equation. The SNR values for the experimental trials are shown in table (7).

Trial no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
S/N (dB)	44.9	48.7	47.7	51.3	46.9	49.4	48.1	50.7	48.9	52.7	51.6	44.2	46.5	46.3	47.0	45.7

Table 7. The SNR values for the experimental trials.

After obtaining the SNR values, the next step was to obtain the average response values of a SNR at low and high levels of each factor and, hence, the effect of each factor on the SNR. The results are shown in tables (8) and (9).

Factor A	Average SNR at level 1	Average SNR at level 2	Average SNR at level 3	Average SNR at level 4	Average SNR at level 5	Average SNR at level 6	Average SNR at level 7	Average SNR at level 8	Effect of the factor	rank
Factor Effect dB	46.83	49.53	48.19	49.43	50.84	47.96	46.41	46.38	4.52	1

Table 8. Average SNR table for factor A.

Factors	Average SNR at level 1 dB	Average SNR at level 2 dB	Effect of the factor dB	Rank
B	47.73	48.69	0.96	6
C	47.10	49.31	2.21	2
D	48.18	48.23	0.05	8
E	48.23	48.46	0.23	7
F	47.41	49.00	1.69	3
G	48.98	47.43	-1.65	4
H	47.55	48.86	1.31	5

Table 9. Average SNR table for factors (B, C, D, E, F, G and H).

Tables (8) and (9) show that factors A and C have a dominant effect on the SNR, followed by factors F, G, H, B, E and D. The main effects plot for the SNR is shown in figure (7).

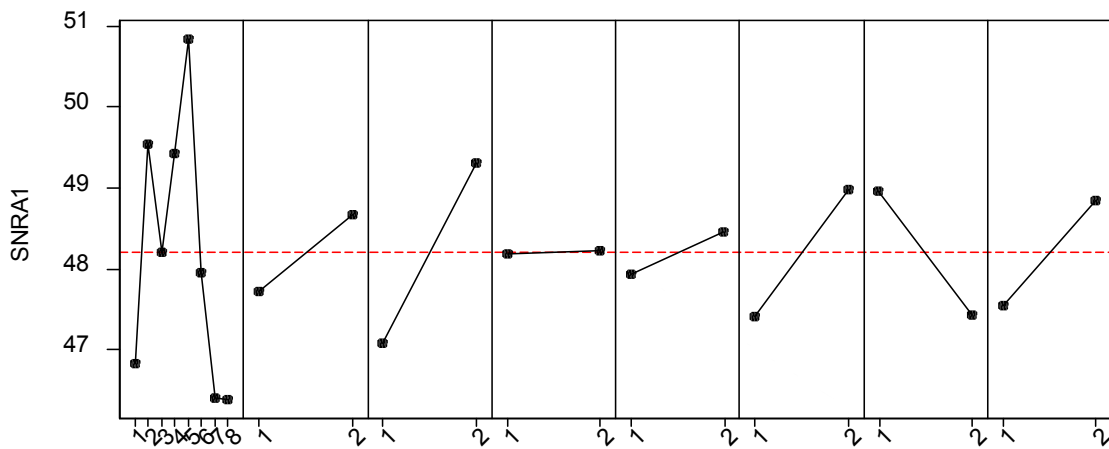


Figure 7. The main effects plot for the S/N ratio.

The calculations of ANOVA for the factors using the Minitab software package are shown in table (10):

Source of variation	Sum of Squares	df	Mean Square	F-ratio
A	37.384	7	5.341	0.88
B	3.529	1	3.529	0.58
C	19.769	1	19.769	3.26
D	0.004	1	0.004	0.00
E	1.129	1	1.129	0.19
F	9.899	1	9.899	1.63
G	9.402	1	9.402	1.55
H	6.679	1	6.679	1.10
error	6.070	1	6.070	1
Total	93.865	15	6.257	

Table 10. ANOVA for the SNR

The second column in Table (10) was calculated using equations 3, 4 and 5, the fourth column with equation 6 and the fifth column from equation 7. The ANOVA table has shown that the most dominant factor effects are D (welding current), E (stud design) and A (welding time). The optimal condition settings of the factors, which will maximize the SNR (i.e., the best control factor settings) based on the SNR are A₅, B₂, C₂, D₂, E₂, F₂, G₁ and H₂.

Trial no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
S N/mm ²	28.8	36.9	33.1	46.7	52.9	77.6	104.3	36.1	68.6	76.3	62.3	40.8	43.2	47.7	62.9	50

Table 11. The standard deviation values for the experimental trials.

The following step studies the effect of the factors on the standard deviation (S) of the process. The standard deviation for each experimental design trial is shown in table (11). The average response effect values of factor A on the standard deviation is shown in table (12). The low and high levels of the other factors are shown in table (13).

Factor A	Average St. at level 1	Average St. at level 2	Average St. at level 3	Average St. at level 4	Average St. at level 5	Average St. at level 6	Average St. at level 7	Average St. at level 8	Effect of the factor	Rank
Factor Effect N/mm ²	32.9	39.6	65.3	70.2	72.4	51.6	45.4	56.7	39.5	1

Table 12. The average standard deviation for factor A.

Factors	Average St at level 1 N/mm ²	Average St at level 2 N/mm ²	Effect of the factor N/mm ²	rank
B	56.98	51.62	-5.36	6
C	54.27	54.32	0.05	8
D	50.56	58.04	7.48	5
E	49.80	58.79	8.99	4
F	46.01	63.1759	16.58	2
G	51.75	56.84	5.09	7
H	59.70	48.9	-10.8	3

Table 13. The average standard deviation for the factors (B, C, D, E, F, G and H).

Tables (12) and (13) show that factors A and F have a dominant effect on the St, followed by factors H, E, D, B and C. The main effects plot for the St is shown in figure (8).

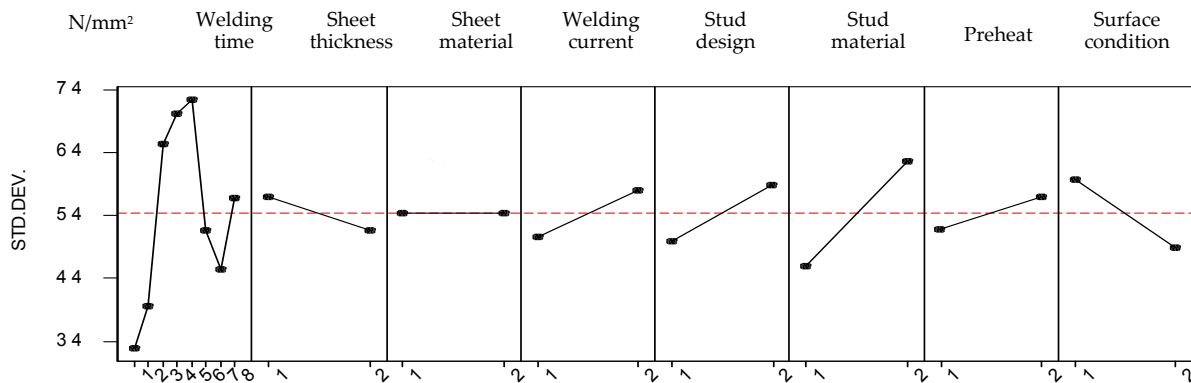


Figure 8. The main effects plot for the standard deviation.

In order to obtain the statistical significance of the effects, the ANOVA table for the standard deviation was performed, as shown in table (14).

Source of variation	Sum of Squares	df	Mean Square	F-ratio
A	2935.4	7	419.34	0.538
B	114.7	1	114.7	0.147
C	0.0	1	0.0	0.00
D	224.1	1	224.1	0.287
E	323.3	1	323.3	0.415
F	1100.6	1	1100.6	1.413
G	103.7	1	103.7	0.133
H	467.2	1	467.2	0.599

Source of variation	Sum of Squares	df	Mean Square	F-ratio
error	778.9	1	778.9	1
Total	6047.9	15	403.193	

Table 14. ANOVA for the standard deviation.

It can be seen from table (13) that C (sheet material) has a large affect on the tensile strength’s standard deviation, while F (Stud material) has less of an effect. The next step was to determine the optimal settings for these factors that will minimize the standard deviation. The optimum conditions (i.e., the best control factor settings) based on the standard deviation are A₁, B₂, C₂, D₁, E₁, F₂, G₂ and H₂. Comparing this result with the result of the SNR setting, it was found that for factors B, C, F and H it was the same. Meanwhile, for factor A it was found that there was a big difference in the values between the two choices and that A₆ gets a balance between the two criteria. For factor D, the effect of this factor on the SNR was very small though it had more of an effect on the standard deviation - as such, the choice for the factor level is D₁. The same holds for factor E and so the choice for this factor level is E₁. For factor G, the effect of this factor on the SNR is less than on the standard deviation - thus, the level of this factor is G₂. After analysing SNR, the standard deviation tables for the best settings for the factor levels were:

$$A_6, B_2, C_2, D_1, E_1, F_2, G_2 \text{ and } H_2$$

Stage (2): Performing the SNR analysis and the standard deviation analysis, the next step was to identify the factor effects that have a significant impact on the mean response. The average response values at each level of factor A and the effects are present in table (15) while the average response values at low and high levels for the other factors and their effects are present in table (16).

Factor A	Average mean at level 1	Average mean at level 2	Average mean at level 3	Average mean at level 4	Average mean at level 5	Average mean at level 6	Average mean at level 7	Average mean at level 8	Effect of the factor	Rank
Factor Effect N/mm ²	231.3	313.1	284.3	336.1	382.3	284.1	222.1	228.6	160.6	1

Table 15. The average response of the welding time control factor.

Factors	Mean response at level 1 N/mm ²	Mean response at level 2 N/mm ²	Effect N/mm ²	Rank
B	270.29	298.16	29.96	6
C	257.07	313.47	56.4	3
D	278.73	291.81	13.08	8
E	278.43	292.11	13.68	7
F	255.61	314.93	59.32	2
G	310.17	260.37	-49.8	4
H	269.55	300.99	31.44	5

Table 16. The average response values at each level of the factors (B, C, D, E, F, G and H) and their effects are shown in figure (7).

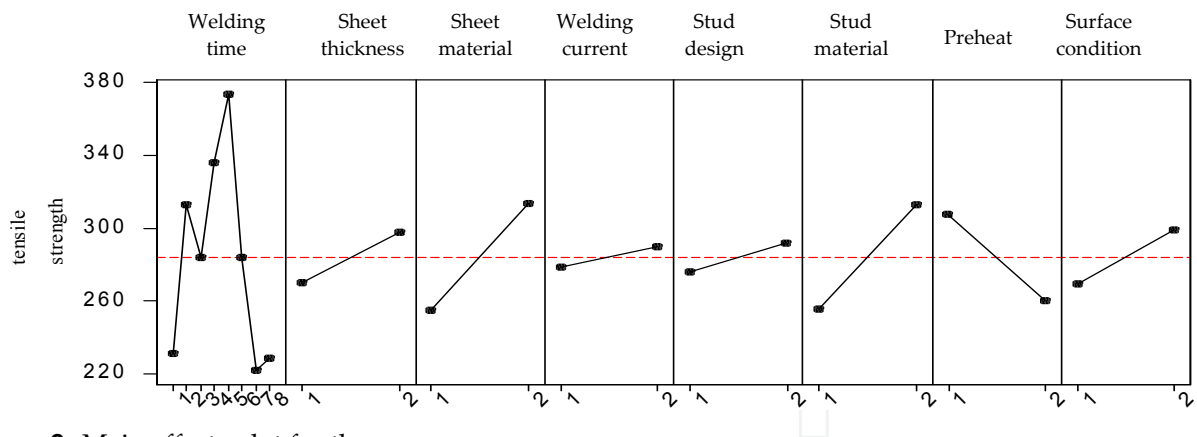


Figure 9. Main effects plot for the mean response.

Figure 7 shows that factors A, C, E and F have a significant impact on the mean response (i.e., the mean tensile strength).

Source of variation	Sum of Squares	Df	Mean Square	F-ratio	% contribution (q)
A	42644	7	6092	42.35	40.11
B	3107	1	3107	21.6	2.92
C	13686	1	13686	95.14	12.87
D	482	1	482	3.35	0.51
E	9099	1	9099	63.25	8.55
F	13095	1	13095	91.04	12.31
G	9099	1	9099	63.25	8.55
H	3444	1	3444	23.94	3.23
error	11651	81	143.84	1	10.95
total	106307	95	1119.02	-	100

Table 17. ANOVA for the response.

It can be seen from table (17) that factor A (welding time) has a large affect on the mean of the stud welding tensile strength (40.11% fraction of importance) - see equations 10 and 11. The factors C (sheet material) and F (stud material) have just (12.87%) and (12.31%) respectively. The added factors B, D, E, G and H can be pooled. A new table without these factors was constructed as table (19). The sum of the squares of the pooled factors was added to the error term. The new mean square of the error term was calculated using equation:

$$V_e = \frac{\sum_i s_i^p + S_e}{\sum_i f_i^p + f_e} \quad (14)$$

where the superscript p indicates the pooled factors.

Since the degree of freedom of factor A is 7 and that of the error term is 86, from F-table at a level of significance of (95% confidence) we obtain $F_{7,86} = 2.11$.

Source of variation	Sum of Squares	df	Mean Square	Variance ratio (F-ratio)	% contribution (q)
A	42644	7	6092	14.2	40.36
C	13686	1	13686	31.91	13.5
F	13095	1	13095	30.53	12.89
error	28779	86	428.86	1	33.25
total	98204	95	1033.72		100

Table 18. The pooled ANOVA for the response.

Because the computed values of the variance ratio in table (18) are bigger than the value from the F-table, there is a 95% degree of confidence that this factor (welding time) has an effect on the stud welding process. For factors C and F, the degree of freedom is 1; as such, $F_{1, 86} = 3.97$, since the computed F-ratio is 31.91 and 30.53 respectively is higher than that from F-table, then these two factors also have an effect on the stud welding process. After identifying the significant factor effects, the next step was to determine the optimal settings for these factors that will bring the mean response as close as possible to the target. The optimum condition (i.e., the best control factor settings) based on the mean response figure was:

$$A_5, B_2, C_2, D_2, E_2, F_2, G_1 \text{ and } H_2$$

Here, factors B, C, F and H are the same as with the last setting. Meanwhile, for factor A there is significant difference when we choose A_5 or A_6 , and when we choose A_5 (the welding time is 0.35 seconds) the tensile strength will be 382.341N/mm² and the standard deviation will be 72.47 N/mm². Furthermore, when choosing A_6 (the welding time is 0.4 seconds) the tensile strength will be 284.110 N/mm² and the standard deviation will be 51.61N/mm². Because the welding time is a continuous value, the researcher’s choice of the new level for this factor will be intermediate between 0.35 and 0.4 seconds, namely $\hat{A}_6 = 0.38$ second. For factor D, the effect for the standard deviation of this factor is more and opposite to that for the mean. As such, the level for this factor is D1. The same applies for factor E1. For factor G, the effect of this factor on the mean is more and opposite that for the standard deviation. Thus, the level of this factor is G1. The factor levels are:

$$\hat{A}_6, B_2, C_2, D_1, E_1, F_2, G_1 \text{ and } H_2$$

In order to arrive at the optimal factor settings, the factor setting is the one which yields the minimum quality loss. The Taguchi quality losses function for the larger-the-better is shown in equation (13). The summarized calculation is shown in table (19).

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$(\hat{y})^2$	299094.4	202216.8	230924.9	125509.6	243914.1	163858.9	174992.3	145438.5	190410.7	83183.4	160655.2	290938.1	256371.3	260776.3	230653.3	276680.6
L(y)/K (money unit/piece)	3.3* 10 ⁻⁶	4.9* 10 ⁻⁶	4.33* 10 ⁻⁶	7.97 *10 ⁻⁶	4.1* 10 ⁻⁶	6.1* 10 ⁻⁶	5.71* 10 ⁻⁶	6.89* 10 ⁻⁶	5.25* 10 ⁻⁶	1.2* 10 ⁻⁵	6.22* 10 ⁻⁶	3.43* 10 ⁻⁶	3.9* 10 ⁻⁶	3.83* 10 ⁻⁶	4.33* 10 ⁻⁶	3.61* 10 ⁻⁶

Table 19. The loss function calculation.

From table (19), run (1) (represented in bold) yields the minimum loss. The optimal factor settings based on the loss-function analysis was, therefore, obtained as:

A_1, F_1, C_1, G_1 and H_1

For factor A, level 1 will yield a very low tensile strength (182.302N/mm^2), so this level is not take. For the three factors F, C and G, the level is the same. For factor H in level 1, the tensile strength is (269.55N/mm^2), while in level 2 it is (300.99N/mm^2). The reduction is also high, so the final optimum setting is:

$\hat{A}_6, B_2, C_2, D_1, E_1, F_2, G_1$ and H_2 .

These factors are summarized in table (20).

factor	\hat{A}_6 : welding time	B_2 :sheet thickness	C_2 :sheet material	D_1 : welding current	E_1 : stud design	F_2 : stud material	G_1	H_2 : Surface cleaning
level	0.38 second	3.175 mm	non- galvanized (K14358 steel)	350 Ampere	Small stud	40CrMnMoS8-6 steel	Preheating	Clean sheet

Table 20. The optimum stud welding condition based on Taguchi methodology optimization.

The predicted mean response at the optimal conditions is estimated only from the significant main and interaction effects. For the study, the main factor effects which have a significant impact on the mean response were A, F, C, G and H. The predicted mean response based on the optimal factor levels of A, F, C, G and H is given by:

$$R = T + (\hat{A}_6 - T) + (C_2 - T) + (F_2 - T) + (G_1 - T) + (H_1 - T) \quad (15)$$

Where

R = predicted mean response at the optimal condition

T = overall mean of all observations in the data

Then: $R = 284.225 + (310.5 - 284.225) + (313.47 - 284.225) + (314.93 - 284.225) + (310.17 - 284.225) + (300.99 - 284.225)$

$$R = 413.185 \text{ N/mm}^2$$

5.2. Experimental conclusions and the confidence interval for the predicted mean response

The confidence interval (CI) is the variation of the estimated result at the optimum condition, calculated as:

$$99\text{percent CI} = R \pm \sqrt{\frac{F \times \text{MSE}}{N_e}} \quad (16)$$

$$\text{MSE} = \text{error variance} = 143.84 \text{ N/mm}^2, F_{1, 96} = 3.96, N_e = \frac{96}{7 + 1 + 1 + 1 + 1 + 1} = 8$$

Therefore, the 99 % confidence interval for the mean tensile strength is given by:

$$99\text{percent}CI = 413.185 \pm \sqrt{\frac{3.96 \times 143.84}{8}}$$

$$= 413.185 \pm 8.43 \text{ N/mm}^2$$

Accordingly, the result at the optimal condition is $413.185 \pm 8.43 \text{ N/mm}^2$ at the 99 % confidence level.

5.3. Confirmation run

A confirmatory run is necessary in order to verify the results from the statistical analysis. A confirmatory run should be carried out to confirm the optimal factor settings obtained from step 10. A sample taken contains ten pieces were produced under the optimal condition that is in table (21):

Sample	1	2	3	4	5	6	7	8	9	10
Tensile strength N/mm ²	443.52	421.32	410.63	390.48	472.40	422.67	398.93	431.88	408.33	524.55

Table 21. The sample tensile strength based on Taguchi methodology optimization

The mean tensile strength from the confirmation run was 432.47 N/mm^2 ; the standard deviation is 39.950 N/mm^2 and the range is 134.07 N/mm^2 . The distribution of this data is explained in figure (10):

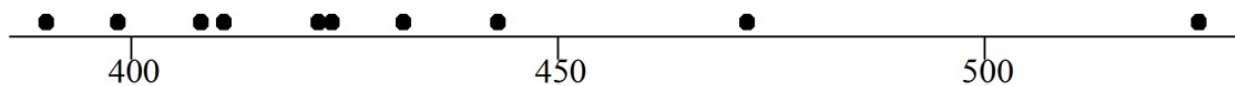


Figure 10. Dot plot for the sample at optimal condition

6. Conclusion

The reduction in the standard deviation was approximately (30.06 %) while for the range the reduction was approximately (29.39%). On the other hand, the increase in the tensile strength mean was approximately (30.84 %). The tensile strength of stud welding process is mostly affected by welding time factor, followed sheet coating factor and stud material factor. The specific conclusions from this study are as follows:

- Dominant factors in the performance of stud welds — the performance of stud welds in this (welding time), (sheet material) and (stud material) dominated the study. In this case, the attached sheet thickness was found to be the dominant variable, with the thicker material demonstrating nearly double the strength compared to using the thinner material. In such cases, thicker materials will have implied higher strengths.

This, in fact, appears to be the case with tensile strengths varying nearly in proportion to the attached sheet's thickness

- Effect of preheating the sheet — preheating has positive effects on increasing the tensile strength while reducing variability.
- Effect of stud design — increasing the stud area appeared to decrease the measures of mechanical performance. This was true even though the levels of internal porosity also increased with the larger studs.
- Effect of sheet thickness — increasing thickness led to increases in the mechanical measure (tensile strength) of the weld quality. The benefits appeared to come from the increased stiffness of the joint as well as the increased peel strengths associated with the thicker material.
- Effect of the sheet material — welding onto galvanized sheets appears to result in substantial porosity in the joint; as such, the non-galvanized sheets have better tensile strength.

7. Future work

There are two tracks to be followed for the use of the proposed Taguchi experimental design. First, to use the output of the experiment as an input for artificial intelligence techniques - like neural networks and fuzzy logic - to get a processes relationship between inputs and outputs. In particular, if this relationship between input and output cannot be represented by lower-order equations, then these techniques can result in accurate factor levels for optimization.

Second, to extend the work of this chapter in multi-objective optimization. This could be optimized with respect to torque testing and bending testing.

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8. References

- Anderson N. S. & Meinheit D. F. (2000) "Design criteria for headed stud groups in shear: part1-steel capacity and back edge effects." *PCI Journal*, pp. 48-75.
- Antony J. & Kaye M. (1999) "Experimental Quality: A Strategic Approach to Achieve and Improve Quality." Kluwer Academic Publishers, London, ISBN: 9780412814402.
- Behrens B., Grub D. & Jenicek A. (2011) "Stud welding within sheet metal working tools." *Prod. Eng. Res. Devel.*, Vol. 5, pp. 283-292.
- Bursi O. S. & Gramola G. (1999) "Behaviour of headed stud shear connectors under low cycle high amplitude displacements." *Materials and structures*, Vol. 32, May, pp. 290-297.
- Buyske S. & Trout R. (2003) "Robust Design and Taguchi Methods." *Journal of Quality Technology*, Vol. 22, No. 1, January pp. 15-22.

- Chambers H. A. (2001) "Principles and Practices of stud welding." *PCI Journal*, September-October, pp. 46-58.
- Conti T., Kondo Y. & Watson G. H. (2003) "Quality into the 21st Century: Perspectives on Quality and Competitive for Sustained Performance." *American Society for Quality*, William A. Tony, USA.
- Eşme U. (2009) "Application of Taguchi method for the optimization of resistance spot welding process." *The Arabian Journal for Science and Engineering*, Vol. 34, No. 2B, pp. 519-528.
- Hsu C., Mumaw J., Thomas J. & Maria P. (2008) "Robotic Stud Welding Process Optimization with Designed Experiment." *Welding Journal*, October, Vol. 87, pp 265-272
- Hsu C. & Mumaw J. with Nelson Stud Welding, Inc. (2011) "Weldability of Advanced High-Strength Steel Drawn Arc Stud Welding." *Welding Journal*, Vol. 90, March, pp. 45-53
- Hsu C., Phillips D., Champney C. & Mumaw J. (2007) "Portable and Intelligent Stud Welding Inverter for Automotive and Sheet Metal Fabrication." *Robotic Welding, Intelligence and Automation*, Vol. 362, pp. 367-374.
- Klarić Š., Kladarić I., Kozak D., Stoić A., Ivandić Ž. & Samardžić I. (2009) "The influence of the stud arc welding process parameters on the weld penetration." Fascicle: *Mechanics, Tribology, Machine Manufacturing Technology*, Serie C, Volume XXIII.
- Lee J. S., Ryu Y. S., Kim N. I., Kim B. J., Kim Y. K. & Kim M. H. (2009) "Stud welding for fixation of cryogenic insulation of membrane tanks in LNG ship building." *Trans. Nonferrous Met. China*, Vol. 19, pp. 271-275. Elsevier Press.
- Miller Welds Electrical Mng. Co., July (2005), www.MillerWelds.com.
- Hamza R. M. A. (2011) "Multi-objective neural network modeling for improving stud arc welding process joining." *Journal of Engineering, Science and Technology*, School of Engineering, Taylor's University Vol. 6, No. 3, 2011, pp. 382-391.
- Ross P. J. (1986) "Taguchi Techniques for Quality Engineering." New York, McGraw-Hill.
- Samardžić I. & Klarić Š. (2007) "On Line Monitoring For Defects In Electric Arc Stud Welding." 11th International Research/Expert Conference *Trends in the Development of Machinery and Associated Technology*. TMT, Hammamet, Tunisia, 5-9 September 2007.
- Schmidt S. R. & Launsby R. G. "Understanding Industrial Designed Experiments." Air Academy Press, Colorado Springs Co., 1992.
- Smith C. S. & Gnudi M. T. (1990) "The PIROTECHNIA of Vannoccio Biringuccio, The classic Sixteenth-Century Treatise on Metals and Metallurgy." Dover Publications Inc., New York.
- Steiner S. H. & MacKay R. J. (2005) "Statistical Engineering: an Algorithm for Reducing Variation in Manufacturing Processes." American Society for Quality ASQ.
- Strigel R. M., Pincheira J. A. & Oliva M. G. (2000) "Reliability of 3/8 in. stud-welded deformed bar anchors subject to tensile loads." *PCI Journal*, November-December 2000, pp. 72-82.
- Taguchi G., Chowdhury S. & Wu Y. (2005) "Taguchi's Quality Engineering Handbook." John Wiley & Sons Inc. New Jersey.
- Taylor J. (2001) "AISC-An Engineer's guide to fabricating steel structure." *Fabrication methods Australian institute of steel construction*, Vol. 1, John Taylor, pp. 107-109.