SIMULTANEOUS OPTIMIZATION OF MULTIPLE QUALITY CHARACTERISTICS IN GAS TUNGSTEN ARC WELDING USING STATISTICAL TECHNIQUES

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بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

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Dedicated to My Loving Parents
Syed Zia-ul-Hassan and Habiba Khanum
who unconditionally provided me
with their unflinching love and support.

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"So praise be to Thee, O Lord, in [Thy] invulnerable Omnipotence, and prudent Forbearance. Bless Muhammad and the family of Muhammad, and let me be among those who thank Thee for Thy bounties and remember Thee for Thy favors." – Du'a Jaushan Al-Sagheer

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LIST OF SYMBOLS

DOE	Design of experiment
GTAW	Gas tungsten arc welding
GMAW	Gas metal arc welding
SMAW	Shielded metal arc welding
SA	Simulated annealing
GA	Genetic algorithm
RSM	Response surface method
CPN	Counter-propagation network
CCD	Central composite design
UAL	Upper allowable limit
LAL	Lower allowable limit
M	Signal
z	Noise factor
x	Control factor
v	Response/output
OA	Orthogonal arrays
ANOVA	Analysis of variance
S/N	Signal to noise ratio
M.S.D	Mean square deviation
η	Signal to noise ratio
η_L	Larger the better signal to noise ratio
y_i	Observed response value for the i_{th} experimental run
η_S	Smaller the better signal to noise ratio
η_T	Nominal the best signal to noise ratio
n	Total number of trials
DOF	Degrees of freedom
r	Repetitions
f_T	Total degrees of freedom
f_e	Degree of freedom of error term

SS_T	Total sum of the squared deviations
η_m	Total mean of the multi-response signal-to-noise ratio
η_j	Mean of the multi-response signal-to-noise ratio for the j-th experiment.
p	The number of experiments
SS_j	Sum of the squared deviations
SS_e	Sum of the squared error
MS_j	Mean square of factor j
PC	Percent contribution
MS_{error}	Variance due to the error term
f_j	The number of degree of freedom for the factor j
HSLA	High strength low alloy steel
C	Carbon
Si	Silicon
Mn	Maganese
P	Phosphorous
S	Sulphur
Cr	Chromium
Mo	Molybdenum
Ni	Nickel
V	Vanadium
TTS	Torch travel speed
L_{ij}	Quality loss for the i_{th} quality characteristic at the j_{th} trial condition
Z_{ij}	Normalized quality loss
L_i^*	Maximum S/N ratio for the ith quality characteristic among all the experimental runs
w_i	weighting factor for the i_{th} quality characteristic
Y_j	Total normalized quality loss in j_{th} experimental run
η_o	Predicted value of multiple S/N ratio at optimal parameter setting
η_i	Average multiple S/N ratio corresponding to i_{th} control factor at optimum parameter level
q	Number of the process parameters that significantly affect the multiple

	quality characteristics.
TNQL	Total normalized quality loss
MSNR	Multi response signal to noise ratio

ABSTRACT

Optimization of Manufacturing Processes presents a significant challenge to modern day manufacturing industries as well as an opportunity to realize significant improvement in quality, cost and consistency of products. Gas Tungsten Arc Welding is one such manufacturing process which finds application in a wide array of industries but still optimized welding parameters are hard to be determined.

This research investigation presents a review of various optimization techniques that have been developed over the years and applied by researchers for the optimization of different manufacturing processes. The review has been concluded with the selection of Taguchi optimization technique which is often the best suited method for GTAW process optimization in industrial environment. Experiments have been designed and conducted based on Taguchi optimization techniques, keeping in view the critical process parameters and required quality attributes. Results have been analyzed using ANOVA and optimum parameter values have been determined. Finally the process has been verified by conducting experiments at selected combination of optimal parameters.

CHAPTER 1

INTRODUCTION

Engineering and fabrication industries operating in present international economic scenario are facing intense challenges in terms of project costs and delivery schedules. Customers are becoming increasingly conscious towards product quality. This challenging environment is presenting engineers with incredible opportunities for developing better understanding towards manufacturing processes and production management methods. Welding in general is considered one of the key fabrication processes in a wide array of industries such as aerospace, shipbuilding, automotive, chemical processing, oil and gas etc.

Hence there is an increased interest in reducing the cost of welding processes by increasing productivity, improving quality, reducing rework/repairs, thus reducing the costs of the overall projects.

1.1 Background

1.1.1 Productivity of Welding Processes

Welding represents one of the most of complex manufacturing processes in terms of number of variables involved and factors contributing to the final output. [1] Despite the recognition of welding as one of the most important fabrication processes in engineering industries, there is little scientific understanding present in productivity measurement, evaluation and control of welding processes. [2]

1.1.2 Cost of Weld Repairs

For welding, repairs and rework represent one of the major factors contributing to overall costs. Cost of welding repairs can often be greater than the cost of producing original welds [3]. These costs can arise from a combination of various factors such as material, labor, production and delivery delays, claims arising from service failures causing accidents or production losses etc. Post welding repair and rework can contribute significantly if welding fabrication is not efficiently controlled.

Economic considerations have forced designers and fabricators to implement better process design practices, which have led to the use of thinner material sections, and therefore a reduction in costs [2]. However this also means an aggravation in distortion related problems in many industries. Distortion of welded structures represents a welding defect, which can incur major costs in terms of repair and rework.

Over the years, the main concern of welding engineers has been reducing production time, weld defects, scrap, improving weld quality and distortion control through process control. Since welding procedures have traditionally been developed based on experience and not governed by a given procedure or calculation, meeting all these objectives right every time is a difficult task. Statistical techniques have been developed to provide solution in such situations whereby initial procedures can be developed based on experience and then can be improved upon using advanced statistical techniques such as DOE etc [4].

A weld program consists of a list of welding parameters developed to achieve a specific weld quality and production output. A change in any parameter will have an effect on the final weld quality. So it is very essential to produce the optimal combination of weld parameters which will improve the weld quality, increase the weld speed and reduce the scrap and rework cost [1].

Many techniques have been proposed to produce the optimal combination of weld parameters. A detailed review of such techniques has been included in the presented work along with the literature review [Chapter 2]

1.2 Research Aims and Objectives

The main purpose of this research study is to identify and apply an appropriate optimization technique to an existing fabrication process comprising use of gas tungsten arc welding (GTAW).

The main objectives of this research study are as follows:

- To study the process of gas tungsten arc welding.

- Identify the various factors which have an effect on the quality of welds produced by the gas tungsten arc weld.
- To study various types of modern optimization techniques which are available for the optimization of processes
- Identify the technique which is best suited for a manufacturing process such as Gas Tungsten Arc Welding.
- Use the chosen technique for the optimization of an existing process.
- Measure the optimized results.

1.3 Research Strategy

The research strategy adopted is shown in Figure 1.2, which is devised to do the following:

- Carry out an exhaustive literature study in order to develop relevant knowledge data base of Gas Tungsten Arc Welding (GTAW) and Optimization techniques.
- Develop an understanding of GTAW process and identify main parameters affecting the process and target quality attributes.
- Conduct experiments as per existing procedure to determine the quality characteristics of the existing process.
- Review the literature in order to analyze the optimization method suitable for optimization of GTAW process.
- Design of experiments as described by the identified optimization techniques.
- Carry out experiments as per designed scheme and evaluate required quality characteristics using appropriate methods.
- Analysis of test results and identification of optimal values for operating parameters.
- Perform experiments using optimal conditions.

- Compare the product quality obtained under optimal condition with those of the existing procedure.

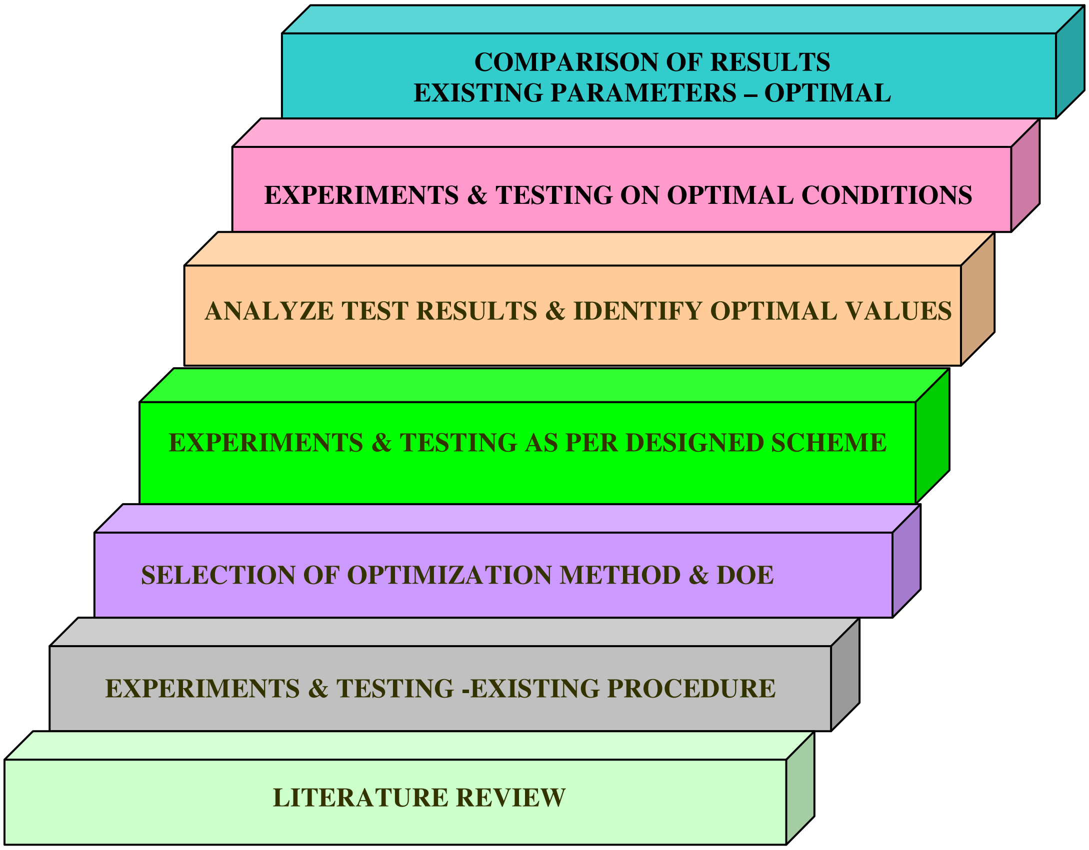


Figure 1.1: The Research Strategy

1.4 Structure of the Thesis

The structure of the thesis has been developed in a very logical and interwoven pattern for an easy understanding of the research study. The format of thesis is in accordance with the "Guidelines for the Preparation of B.E. Project Report / MS Thesis", issued by the National University of Sciences and Technology (NUST), Rawalpindi, Pakistan.

Following the first chapter which includes the background of the problem along with objective of thesis project, chapter 2 includes gas tungsten arc welding (GTAW) process, problem description, review of various popular optimization techniques, application of these techniques to welding processes in general and to GTAW process in particular by different investigators.

Once the optimization technique has been identified, experiments can be designed taking into account all the important factors that can affect the productivity of GTAW process. A detailed description of experimental design has been included in chapter 3 which is titled “experimental work”. The chapter also describes in detail all the materials, equipment, testing specimen and procedures used during experimental work.

Chapter 4 presents results of various experiments carried out during testing. A detailed analysis of these results using ANOVA has also been presented which leads to the identification of optimal values for different parameters. Results of the experiments conducted under optimal conditions as well as comparison with original results (carried out under existing procedures) has also been included.

A brief discussion on results obtained by following the experimental design has been presented in chapter 5.

The research has been concluded in chapter 6 while recommendations for future work have been summarized in chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The gas tungsten arc welding (GTAW) process originally was created in the 1940s to weld magnesium and aluminum alloys for aircraft applications. It was developed because a welding method was needed that performed better on these materials than did shielded metal arc welding (SMAW)[1].

Gas Tungsten Arc Welding, usually referred to as TIG welding (Tungsten Inert Gas welding), is a welding procedure using a non-consumable electrode, shielding gas (usually inert) and filler wire fed by hand. The electrode is mounted coaxially in the center of the gas nozzle. While the arc is maintained between the work piece and electrode, the inert gas shields the molten weld pool from atmospheric combinations. The filler metal comes in rods of various diameters and metal compositions [5].

2.2 Welding Procedures

2.2.1 The Equipment

A typical welding system usually consists of the following elements:

1. Welding power supply.
2. Weld controller.
3. Welding torch.
4. Tungsten electrode.

2.2.2 Operation

Manual gas tungsten arc welding is often considered the most difficult of all the welding processes commonly used in industry. Because the welder must maintain a short arc length, great care and skill are required to prevent contact between the electrode and the work piece. Unlike most other welding processes, GTAW normally requires two hands, since most applications require that the welder manually feed a filler metal into the weld area with one hand while manipulating the welding torch in the other. However, some welds combining thin materials (known as autogenously or fusion welds) can be accomplished without filler metal; most notably edge, corner, and butt joints [5].

To strike the welding arc, a high frequency generator provides a path for the welding current through the shielding gas, allowing the arc to be struck when the separation between the electrode and the work piece is approximately 1.5–3 mm (0.06–0.12 in). Bringing the two into contact in a "touch start" ("scratch start") also serves to strike an arc. This technique can cause contamination of the weld and electrode. Once the arc is struck, the welder moves the torch in a small circle to create a welding pool, the size of which depends on the size of the electrode and the amount of current. While maintaining a constant separation between the electrode and the work piece, the operator then moves the torch back slightly and tilts it backward about 10–15 degrees from vertical. Filler metal is added manually to the front end of the weld pool as it is needed [6].

Welders often develop a technique of rapidly alternating between moving the torch forward (to advance the weld pool) and adding filler metal. The filler rod is withdrawn from the weld pool each time the electrode advances, but it is never removed from the gas shield to prevent oxidation of its surface and contamination of the weld. Filler rods composed of metals with low melting temperature, such as aluminum, require that the operator maintain some distance from the arc while staying inside the gas shield. If held too close to the arc, the filler rod can melt before it makes contact with the weld puddle. As the weld nears completion, the arc current is often gradually reduced to allow the weld crater to solidify and prevent the formation of crater cracks at the end of the weld [6, 7].

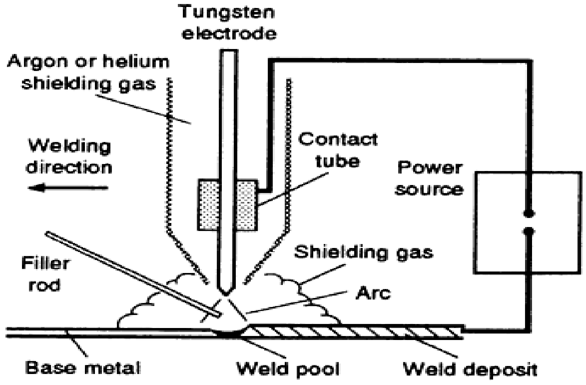


Figure 2.1: A Schematic Diagram of Basic Operation of GTAW [5]

2.2.3 Welding Parameters [8]

Besides the equipment, one of the most important aspects of the GTAW process is the welding parameters used. The important GTAW parameters are arc current, arc voltage, torch travel speed and wire feed speed.

2.2.3.1 Arc Current

As a general statement, arc current controls the weld penetration, the effect being directly proportional, if not somewhat exponential. Arc current also affects the voltage, with the voltage at a fixed arc length increasing in proportion to the current. For this reason, to keep a fixed arc length, it is necessary to change the voltage setting when the current is adjusted.

The process can be used with either direct or alternating current, the choice depending largely on the metal to be welded. Direct current with the electrode negative offers the advantages of deep penetration and fast welding speeds, especially when helium is used as the shield. Helium is the gas of choice for mechanized welding. Alternating current provides a cathodic cleaning (sputtering) which removes refractory oxides from the joint surfaces of aluminum and magnesium, allowing superior welds to be made. In this case, argon must be used for the shield because sputtering cannot be obtained with helium. Argon is the gas of choice for manual welding whether used with direct current or alternating current.

A third power option also is available, that of using direct current with the electrode positive. This polarity is used only rarely because it causes electrode overheating.

2.2.3.2 Arc Voltage

The voltage measured between the tungsten electrode and the work is commonly referred to as the arc voltage. Arc voltage is a strongly dependent variable, affected by the following:

1) Arc current
2) Shape of the tungsten electrode tip
3) Distance between the tungsten electrode and the work
4) Type of shielding gas

The arc voltage is changed by the effects of the other variables, and is used in describing welding procedures only because it is easy to measure. Since the other variables such as the shield gas, electrode, and current have been predetermined, arc voltage becomes a way to control the arc length, a critical variable that is difficult to monitor. Arc length is important with this process because it affects the width of the weld pool; pool width is proportional to arc length. Therefore, in most applications other than those involving sheet, the desired arc length is as short as possible.

Of course, recognition needs to be given to the possibility of short circuiting the electrode to the pool or filler wire if the arc is too short. However, with mechanized welding, using a helium shield, DCEN power, and a relatively high current, it is possible to submerge the electrode tip below the plate surface to produce deeply penetrating but narrow welds at high speeds. This technique has been called buried arc.

When arc voltage is being used to control arc length in critical applications, care must be taken to observe the other variables, which affect arc voltage. Among them are electrode and shielding gas contaminants, improperly fed filler wire, temperature changes in the electrode, and electrode erosion. Should any of these change enough to affect the arc voltage during mechanized welding, the arc length must be adjusted to restore the desired voltage.

2.2.3.3 Torch Travel Speed

Travel speed affects both the width and penetration of a gas tungsten arc weld. However, its effect on width is more pronounced than that on penetration. Travel speed is important because of its effect on cost. In some applications, travel speed is defined as an objective, with the other variables selected to achieve the desired weld configuration at that speed. In other cases, travel might be a dependent variable, selected to obtain the weld quality and uniformity needed under the best conditions possible with the other combination of variables. Regardless of the objectives, travel speed generally is fixed in mechanized welding while other variables such as current or voltage are varied to maintain control of the weld.

2.2.3.4 Wire Feed Speed

In manual welding, the way filler metal is added to the pool influences the number of passes required and the appearance of the finished weld.

In machine and automatic welding, wire feed speed determines the amount of filler deposited per unit length of weld. Decreasing wire feed speed will increase penetration and flatten the bead contour. Feeding the wire too slowly can lead to undercut, centerline cracking, and lack of joint fill. Increasing wire feed speed decreases weld penetration and produces a more convex weld bead.

The welding process is a multi -input and multi-output joining process in which the quality of joint is closely associated with welding parameters therefore identifying the suitable combinations of process input parameters to produce the desired output parameters require many experiments[9]. Therefore objective of present work is to select a optimization strategy that would produce the best possible optimal combination of GTAW parameters (input parameters) and quality attributes (output parameters) with least number of experiments

2.3 Problem description

The investigation has taken up to address problems encountered in an industrial manufacturing process (based on GTAW welding) with requirements for high levels of quality control. Welding procedures were initially developed based on past experience and critical parameters adjusted to achieve acceptable quality level during test run. However weld defects were frequently observed (some of them are shown in fig 2.2 and 2.3) during actual production run which required repairs, reworks and rectification along with some rejections. This resulted in loss of quality levels, manufacturing process efficiency as well as an increase in cost of project.

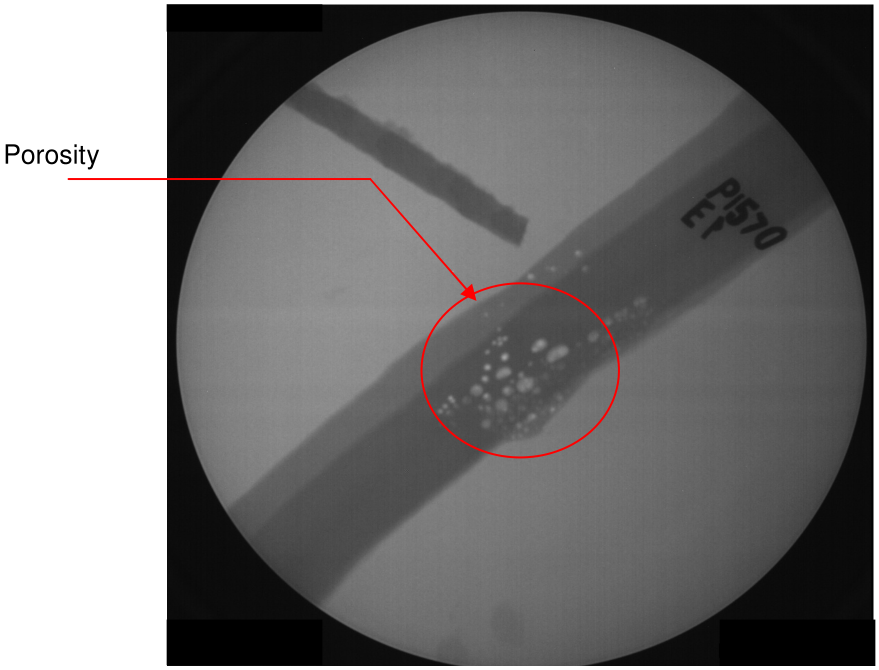


Figure 2.2: Common Defect - Porosity

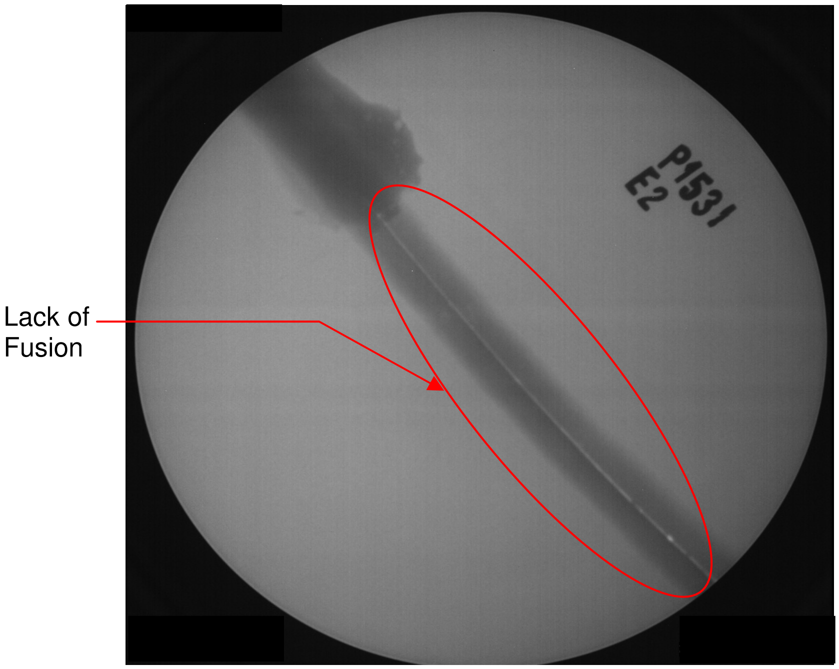


Figure 2.3: Common Defect - Lack of Fusion

2.4 Various Popular Optimization Methods for Determining the Optimal Welding Parameters

Various popular optimization approaches used to optimize the welding parameters are shown in figure 2.4

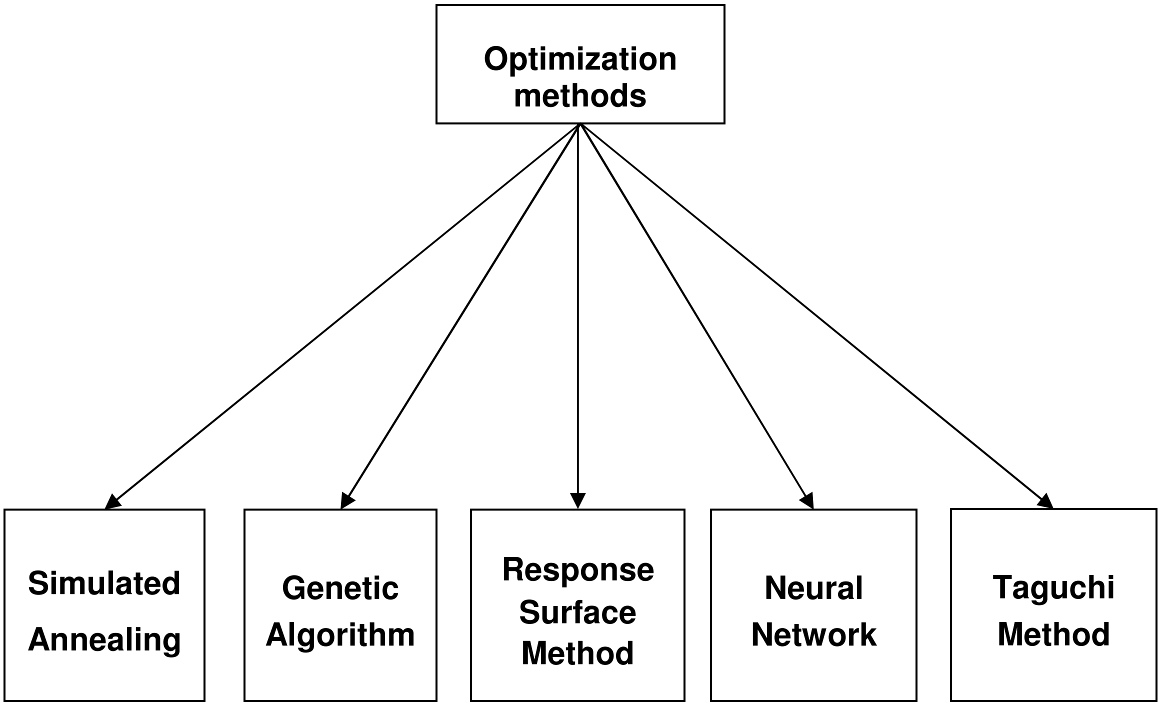


Figure 2.4: Various Popular Optimization Methods for Determining the Optimal Welding Parameters

The details regarding how these optimization methods have been used by various investigators to optimize the welding parameters are discussed below

2.4.1 Simulated Annealing

SA is a technique used to find a good solution to an optimization problem by trying random variations of the current solution. A worse variation is accepted as the new solution with a probability that decreases as the computation proceeds. The slower the cooling schedule, or rate of decrease, the more likely the algorithm is to find an optimal or near-optimal solution.[10] In Artificial Intelligence, simulated annealing is used to help a neural network avoid local minima in its energy function[11]. Both of these phenomena have been used in [12] where neural networks and simulated annealing (SA) algorithm has been applied to model and optimize the gas tungsten arc welding (GTAW) process. The relationships between welding process parameters and weld pool features are established based on neural networks. In this study, the counter-propagation network (CPN) is selected to model the GTAW process due to the CPN equipped with good learning ability. An SA optimization algorithm is then applied to the CPN for searching for the welding process parameters with optimal weld pool features.

2.4.2 Response surface methodology (RSM):

RSM is a sequential procedure. Essentially it starts with a factorial experiment in a localized region of response surface. This method is used to determine a series of experimental conditions yielding increasing values of response. When the yield of the experimental conditions shows reductions instead of additional increases, a second factorials experiment is designed, and a series of experimental conditions is generated and tested. This procedure is repeated until the experimental response can be improved very slowly and only by modest quantities [4]. At this point the region of the optimum is reached and a more elaborate factorial design is used to identify the optimum. This response surface method has been used in [13] to determine the optimal factors of Gas Metal Arc Welding (GMAW) process. Firstly, a full factorial (24) experimental design which consisted of 2 levels was used. All four factors, which were current, volt, speed and gas shielded, were searched to find the important parameters, which exhibited the significant tensile of weldment. After that, the Central Composite Design (CCD) experimental design was used to analyze data and find out the optimization of important parameters.

2.4.3 Genetic Algorithm (GA)

GA is a search technique used in computing to find exact or approximate solutions to optimization and search problems. Genetic algorithms are a particular class of evolutionary algorithms (also known as evolutionary computation) that use techniques inspired by evolutionary biology such as inheritance, mutation, selection and crossover (also called recombination)[14].In [15] the possibility of using genetic algorithms is utilized as a method to decide near-optimal settings of a GMAW welding process . The problem was to choose the near-best values of three control variables (welding voltage, wire feed rate and welding speed) based on four quality responses (deposition efficiency, bead width, depth of penetration and reinforcement), inside a previous delimited experimental region. The search for the near-optimal was carried out step by step, with the GA predicting the next experiment based on the previous, and without the knowledge of the modeling equations between the inputs and outputs of the GMAW process. The

GAs was able to locate near-optimum conditions, with a relatively small number of experiments. However, the optimization by GA technique requires a good setting of its own parameters, such as population size, number of generations, etc. Otherwise, there is a risk of an insufficient sweeping of the search space.

2.4.4 Taguchi Method

Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan has developed a method based on "ORTHOGONAL ARRAY" experiments which gives much reduced "variance" for the experiment with "optimum settings "of control parameters. Thus the marriage of Design of Experiments with optimization of control parameters to obtain BEST results is achieved in the Taguchi Method [16]. The taguchi method is a systematic application of design and analysis of experiments for the purpose of designing and improving product quality [17].In recent years taguchi method has become a powerful tool for improving productivity during research and development so that high quality products can be produced quickly and at low cost [18]

Several investigators have used Taguchi method for optimization of welding parameters in various welding processes such as TIG [19], SAW [20] etc. A range of welding process related quantitative parameters such as Tensile Strength, hardness values as well as qualitative parameters such weld bead geometry have been optimized

2.5 Selection of Optimization Strategy

A review of the above briefly explained methods would reveal that principle focus of each of these methods is the determination of best possible optimal solution in the least number of experiments. It has also been observed from recent investigative work by different researchers that several mathematical models have been developed to correlate welding performance with welding parameters [21-24]. To properly select welding parameters, an objective function with constraints is formulated to solve optimal welding parameters using optimization techniques [24]. However, considerable knowledge and experience are required to use this approach. Furthermore, numerous welding experiments have to be performed to build the mathematical models. In this study, an alternative approach based on the Taguchi method [25-27] is used as an efficient method to determine the optimal welding parameters. The chosen optimization strategy (Taguchi method) has several advantages which are discussed later in detail. The steps of present study of taguchi optimization are presented in figure2.5

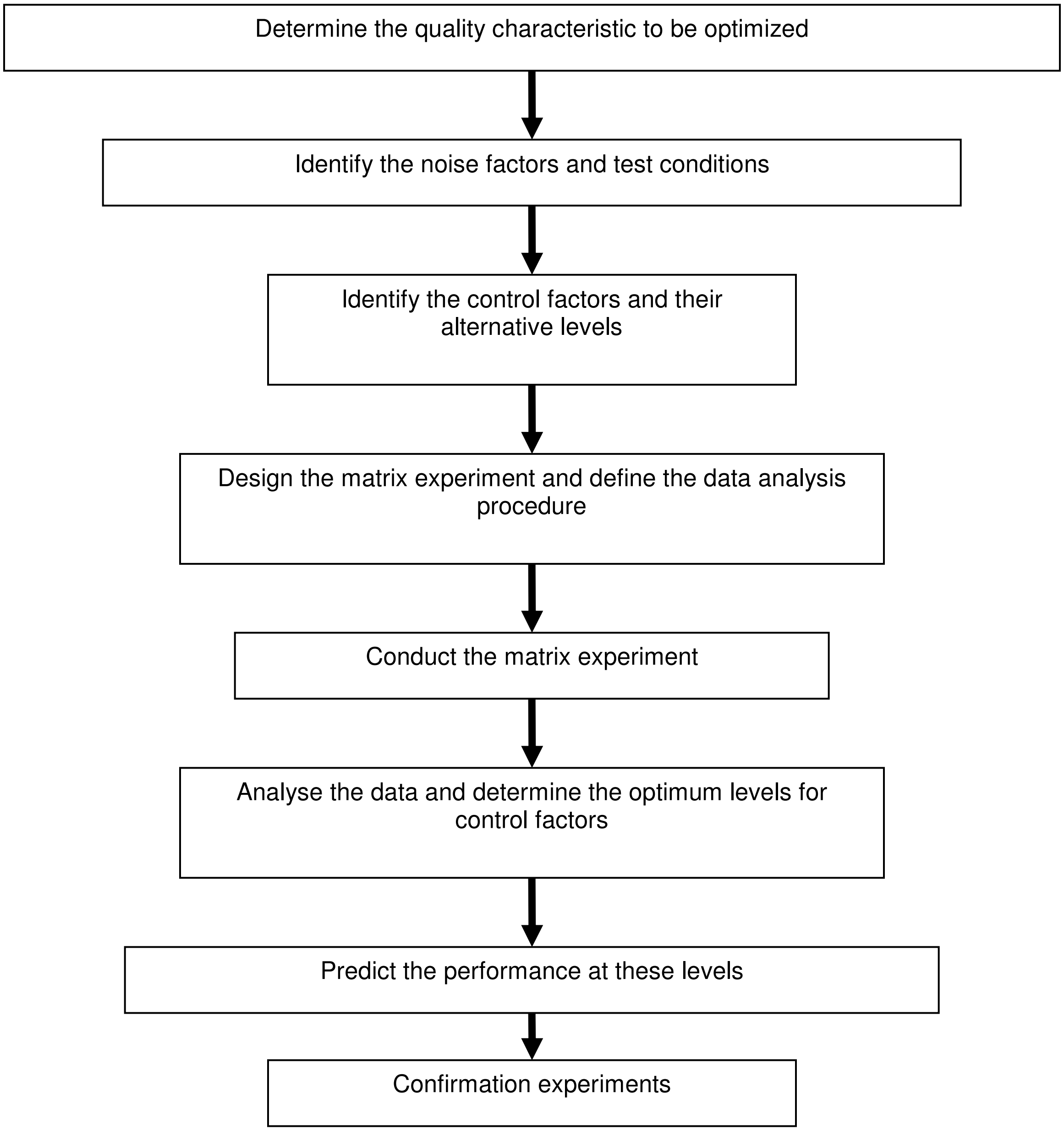


Figure 2.5: Flow Chart of Taguchi method [28]

2.5.1 Advantages of Taguchi Method [29]

In the present economic scenario, processing costs and problems of repeatability can stall development of new projects and products right at the profit line. Marginal improvements in the control of manufacturing processes, although useful in the short term, will not provide the needed levels of quality, reliability, or economy of production. Figure 2.6 depicts the shift in approaches used to ensure product quality as a function of time. Taguchi methods belong to the class of approaches that attempt to ensure quality through design, in this case through the identification and control of critical variables (or noises) that cause deviations to occur in the process/product quality.

Taguchi methods refer to techniques of quality engineering that embody both statistical process control (SPC) and new quality related management techniques. Most of the attention and discussion on Taguchi methods has been focused on the statistical aspects of the procedure; it is the conceptual framework of a methodology for quality improvement and process robustness that needs to be emphasized. The entire concept can be described in two basic ideas:

1. Quality should be measured by the deviation from a specified target value, rather than by conformance to preset tolerance limits

2. Quality cannot be ensured through inspection and rework, but must be built in through the appropriate design of the process and product

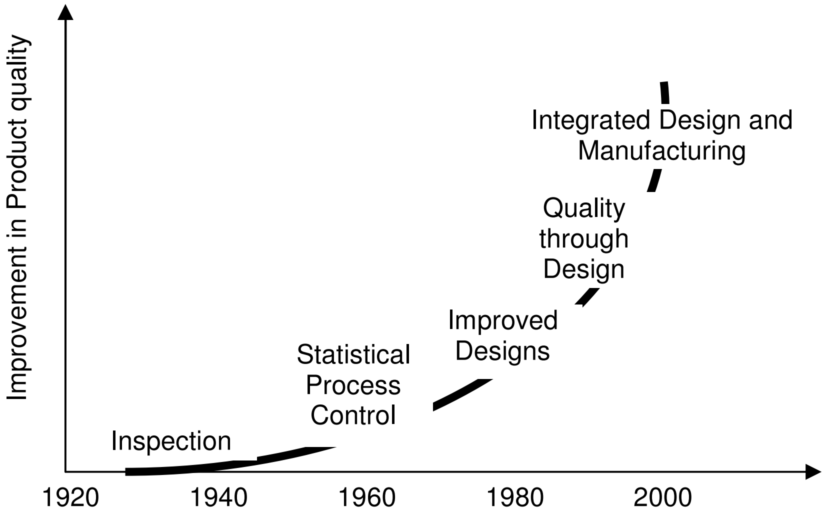


Figure 2.6: The Evolution of Quality Control [29]

The first concept underlines the basic difference between Taguchi methods and the SPC methodology. Whereas SPC methods emphasize the attainment of an attribute within a tolerance range and are used to check product/process quality, Taguchi methods emphasize the attainment of the specified target value and the elimination of variation (Figure: 2.7). In conjunction with the second concept, this assumes great significance for manufacturing since Taguchi methods emphasize that control factors must be optimized to make them insensitive to manufacturing transients through design, rather than by trial and error. SPC allows for faults and defects to be eliminated (if detected) after manufacture, whereas what is really needed is a methodology that prevents their occurrence. In this case, the methodology is the use of Taguchi methods. This then presents a powerful tool for any manufacturing process within which there is an inherent variability due to raw material quality and/or noise in the process environment itself.

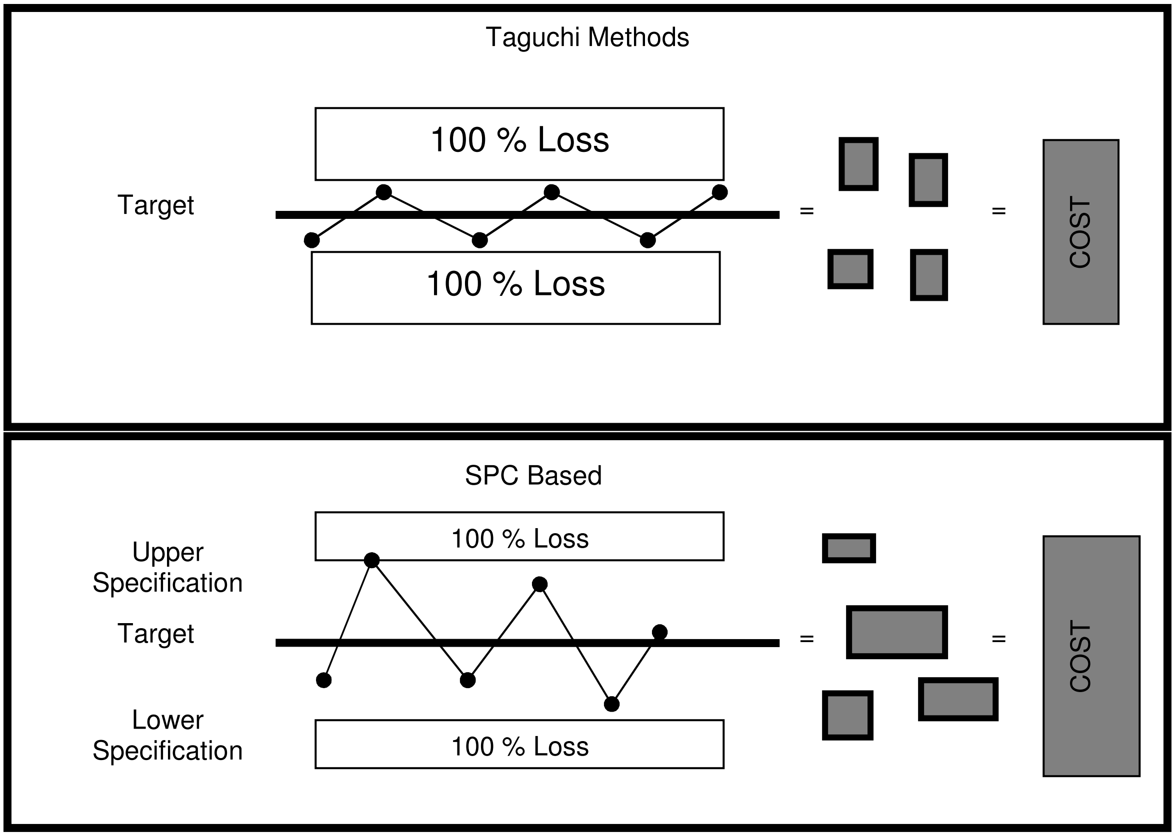


Figure 2.7: A Comparison of Methodologies [29]

Thus the advantage of Taguchi method is that it emphasizes a mean performance characteristic value close to the target value rather than a value within certain specification limits, thus improving the product quality. Additionally, Taguchi's method for experimental design is straightforward and easy to apply to many engineering situations, making it a powerful yet simple tool. It can be used to quickly narrow down the scope of a research project or to identify problems in a manufacturing process from data already in existence. Also, the Taguchi method allows for the analysis of many different parameters without a prohibitively high amount of experimentation. In this way, it allows for the identification of key parameters that have the most effect on the performance characteristic value so that further experimentation on these parameters can be performed d and the parameters that have little effect can be ignored

2.5.2 The Design Cycle

According to Taguchi philosophy through the proper design of a system, the process can be made insensitive to variations, thus avoiding the costly eventualities of rejection and/or rework [29]. In order to determine and subsequently minimize the effect of factors that cause variation, the design cycle is divided into three phases,

1) System design.
2) Parameter design.
3) Tolerance design.

System Design is the phase to generate a basic prototype design that performs the function of the product with minimum deviation from target performance values. In this phase new concepts, ideas and methods are developed using current technology processes, materials and engineering methods to provide new or improved products to consumers. [4]

Parameter Design is the phase where methods of experimental design are used to identify settings of product and process parameters in such a way that the sensitivity of the desired product characteristics to changes in the controllable environmental variables is minimized. [30]

Tolerance design is the phase to study each parameter or factor by trading off quality loss and cost. [30]

Of all these phases the parameter design phase, which is actually an offline quality control method, is the most important stage for achieving high quality without any substantial increase in the cost.[4]

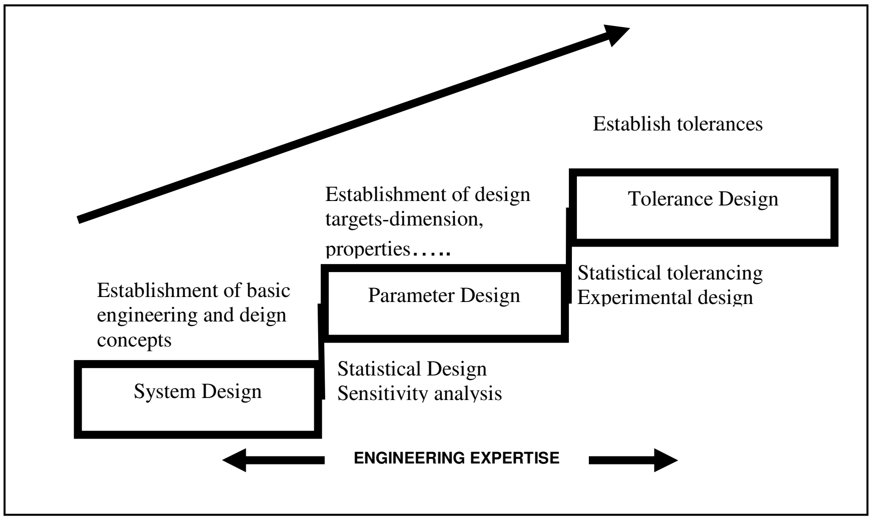


Figure 2.8: Stages in Design Cycle [29]

2.5.3 Loss Function

The concept of the 'total loss function' employed by Taguchi has forced engineers and cost accountants to take a serious look at the quality control practices of the past.

The concept is simple but effective. Quality is defined as 'the total loss imparted to the society from the time a product is shipped to the customer'[31]. The loss is measured in monetary terms and includes all costs in excess of the cost of a perfect product. The definition can be expanded to include the development and manufacturing phases of a product.

A poorly conceived and designed product begins to impart losses to society from the embryonic stage and continues to do so until steps are taken to improve its functional performance. There are two major categories of loss to society with respect to product quality. The first category relates to the loss incurred as a result of harmful effects to society, i.e., pollution, and the second relates to the losses arising because of excess variation due to functional performance [32]

The conventional method of computing the cost of quality is based on the number of parts rejected and reworked. This method of quality is incapable of distinguishing between two samples, both within the specification limits, but with different distributions of the target properties. Figure 2.9 shows the conventional method and Taguchi's view of the loss function. This graph depicts the loss function as a deviation from an ideal or target value of a given design parameter [33]

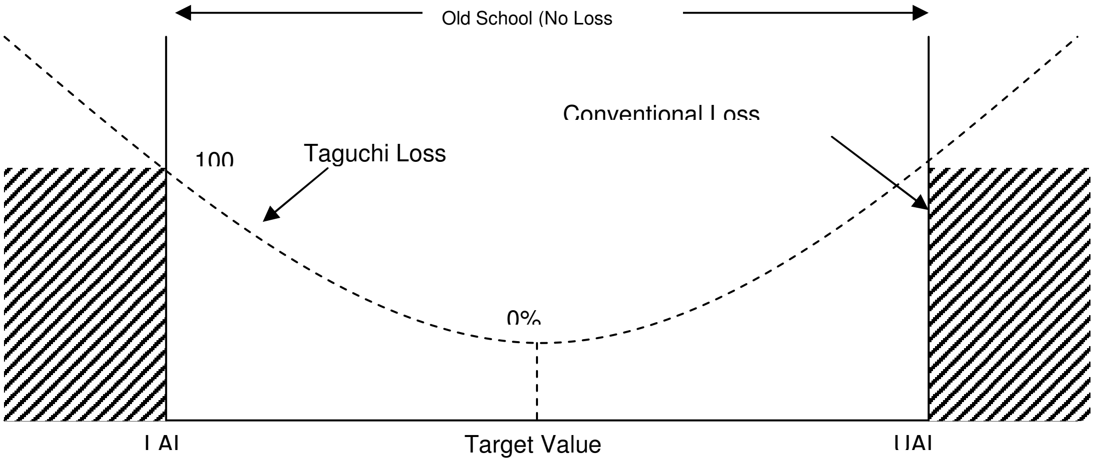


Figure 2.9: Taguchi Loss Function vs. Conventional Loss Function [32]

Here the target value or the most desirable value of the parameter under consideration.

This parameter may be a critical dimension or any characteristic that contributes to the customer's definition of quality. How this ideal value of the parameter is obtained and how significant this value is in achieving quality goals will be evident later.

The Upper Allowable Limit (UAL) and the Lower Allowable Limit (LAL) represent upper and lower limits of a design parameter, respectively. Normally the product is functionally acceptable if the value of the specified parameter is within the range between the UAL and LAL limits. No societal loss is assumed to occur and the product is shipped to the customer. Outside of these limits as shown by the cross-hatched region, 100% functional deterioration occurs and the product is either discarded or subjected to salvage operations. Every attempt is made to control the manufacturing process to maintain the product within these limits. According to Taguchi, there is no sharp cutoff in the real world [34]. Performance begins to gradually deteriorate as the design parameter deviates from its optimum value. Therefore, the loss function should be measured by the deviation from the ideal value. This function is continuous and shown by the dotted line in Figure

2.7. Product performance begins to suffer when the design parameters deviate from the ideal or the target value. Taguchi's definition clearly puts more emphasis on customer satisfaction, whereas previously all definitions were related to the producer. Optimum customer satisfaction can be achieved by developing products which meet the target value on a consistent basis. It may be worthwhile to mention that Taguchi allows for more than 100% loss imparted by a product. Such cases can occur when a subsystem results in the failure of the entire system or when a system fails catastrophically. The single most important aspect of Taguchi's quality control philosophy is the minimization of variation around the target value.

2.5.4 Classification of Factors and Choice of Quality Characteristics

For manufacturing process optimization problems, the following factors are of interest to experimenters: [4]

1) Control Factors
2) Noise Factors
3) Signal Factors

A block diagram is shown in Figure 2.10 that depicts those factors that influence the response (quality characteristic) of a product or process. In the block diagram y stands for the response. This diagram represents the case for only a single response, but the extension to multiple responses is straightforward. The output, y, can be described in terms of these inputs.

Control factors are those factors that can be controlled easily during actual production conditions. For example, voltage, temperature and time are control factors; these are also called design parameters. It is the objective of the design activity to determine the best levels of these factors to achieve product/ process robustness. In this sense robustness refers to making products/ processes insensitive to various sources of variation.

Although control factors are studied to establish their ideal values to accomplish the objective of the experiment, it is useful to classify the effects of control factors on the quality characteristic.

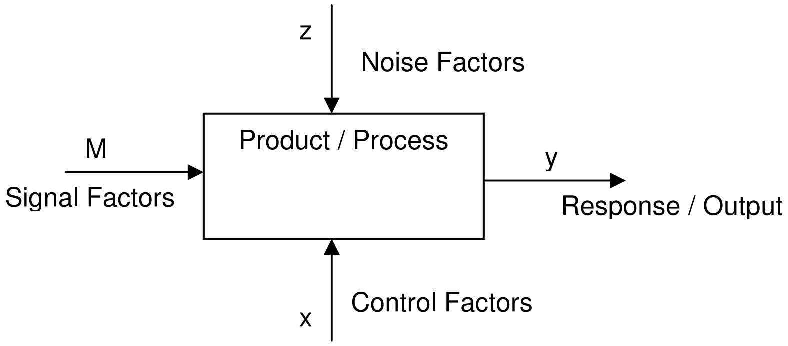


Figure 2.10: Response from Factor Influence [35]

2.5.5 Noise Factors

Noise factors are those factors that are difficult to control during actual production but may be controllable during experimental design. These factors cause the performance characteristic of a product to deviate from its target or nominal value. The levels of the noise factors change from one unit to another, from one environmental condition to another and from time to time. Only the statistical characteristics such as the mean and variance of noise factors can be known or specified, the actual values in situations cannot be known.

2.5.6 Experiment Design Strategy

To determine the relationship between the output, y, and the signal, control and noise factors normally requires experimentation. In laying out a test and development strategy, simple logic will usually be sufficient to establish all possible combinations of factors along with allowable ranges for each of the factors involved. For engineering projects involving many factors, the number of possible combinations is prohibitively large. In addition, higher order interactions among the influencing factors may be needed for specific projects.[33]

For a single two-level factor A, two experiments are required to study the effects, A_1 and A_2, then two experiments become necessary, one at level $A_1$and one at level A_2.For two factors A and B, each at two levels (A_1, A_2 and B_1, B_2), there are 4 combinations, since when A is held at A_1, B can assume B_1 and B_2 and when A is held at A_2, B can again assume B_1 andB_2.

Symbolically these combinations are expressed as:

$$A_1\,(B_1B_2),\ A_2(B_1B_2) \text{or as } A_1B_1, A_1B_2, A_2B_1, \text{ and } A_2B_2 \qquad Eq.\ (\ 2.1)$$

With three factors, each at two levels, there are 2^3(8) possible experiments. If A, B, and C corresponds to these factors, the 8 experiments can be expressed as:

$$A_1B_1C_1,\ A_1B_1C_2\ ,\ A_1B_2C_1,\ A_1B_2C_2,\ A_2B_1C_1,\ A_2B_1C_2,\ A_2B_2C_1,\ A_2B_2C_2 \qquad Eq.(\ 2.2)$$

A full factorial design will identify all possible combinations for a given set of factors. Since most experiments in industry involve a significant number of factors, a full factorial experiment results in a large number of experiments. For example, in an experiment involving seven factors, each at two levels the total number of combinations will be 128 (2^7). To reduce the number of experiments to a practical level, only a smallest from all the possibilities, is selected. A customary method of reducing the number of test combinations is to use what are known as partial factorial experiments. [36] Although this method is well known, there are no general guidelines for its application or the analysis of results by performing the experiments.

Taguchi constructed a special set of general designs for factorial experiments that cover many applications. The special set of general designs consists of orthogonal arrays (OA). The use of these arrays helps to determine the least number of experiments.[30]

Taguchi's approach complements these two important areas. First, a clearly defined set of OAs, each of which can be used for many experimental situations are stated. Second, he devised a standard method for the analysis of results. The combination of standard experimental design techniques and analysis methods in the Taguchi approach produces consistency and reproducibility rarely found in any other statistical methods[4]

2.5.7 Orthogonal Arrays

Taguchi constructed a special set of orthogonal arrays (OA) to lay out his experiments. The use of Latin square orthogonal arrays for experimental design dates back to the time of Worid War n.[37] By combining the orthogonal Latin squares in a unique manner, Taguchi prepared a new set of OAs to be used for a number of experimental situations. A common OA for 2- level experiment is shown in Table 2.1.

This array, designated by the symbol L_8, is used to design experiments involving up to seven 2 level factors. A two level factor is a factor that has two values. This is a parameter that is defined in the experiment, by the experiment designer. Each row represents a trial condition with factor levels indicated by the numbers in the row. The vertical columns correspond to the factors specified in the study.[38]

Table 2.1: L8 Orthogonal Array

	A	B	C	D	E	F	G
Trial							
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Each column contains four level 1 and four level 2 conditions for the factor assigned to the column. Two 2 level factors combine in four possible ways such as (1, 1), (1, 2), (2, 1) and (2,2). When two columns of an array form these combinations the same number of times, the columns are said to be balanced or orthogonal. Any two columns of an L_8 (2^7) have the same number of combinations of (1,1), (1, 2), (2,1) and (2,2). Because of this, all seven columns of an L are orthogonal to each other.

The OA facilitates a design of experiments process. To design an experiment is to select the most suitable orthogonal array, assign the factors to the appropriate columns and finally, describe the combinations of the individual experiments, called the trial conditions. Assuming that there are at most seven 2 level factors , the factors can be denoted as A, B, C, D, E, F and G and assigned to the columns 1, 2, 3, 4, 5, 6, and 7 respectively of L_8. The table identifies the eight trials needed to complete the experiment and the level of each factor for each trial run. Descriptions of the experiment are determined by reading numerals 1 and 2 appearing in the rows of the trial runs. A factorial experiment would require 2 or 128 runs, but would not provide appreciably more information.

The array forces all experimenters to design almost identical experiments. Experimenters may select different designations for the columns but the eight trial runs will include all combinations independent of column definition. This feature of the OA assures consistency of the experiment regardless of the experimenter. The total number of full factorial experiments possible for different numbers of factors at 2 or 3 levels and the corresponding suggested Taguchi number of experiments is shown in Table 2.2.

Taguchi has established OAs to describe a large number of experimental situations. Experimental designs by OAs are attractive because of experimental efficiency, but there are some potential tradeoffs. Generally speaking, OA experiments work well when there is minimal interaction among factors. For example, the factor influences on the measured quality objectives are independent of each other and are linear. [39] When the outcome is directly proportional to the linear combination of individual factor effects, OA design identifies the optimum condition and estimates performance at this condition accurately. If the factors interact with each other and influence the outcome in a nonlinear fashion, there is still a good chance that the optimum condition will be identified accurately, but the estimate of performance at the optimum can be significantly off .The degree of accuracy in performance estimates will depend on the degree of complexity of interactions among all of the factors.[30]

Table 2.2: Full Factorial DOE versus Taguchi DOE

Factors	Levels	Factorial Design	Taguchi
2	2	4 (2^2)	4
3	2	8 (2^3)	4
4	2	16 (2^4)	8
7	2	128 (2^7)	8
15	2	32,768 (2^{15})	16
4	3	81 (3^4)	9

2.5.8 Analysis of Results

In the Taguchi method, the results of the experiments are analyzed to achieve one or more of the following three objectives:[38]

1) To establish the best or optimum condition for a product or a process,
2) To estimate the contribution of individual factors,
3) To estimate the response under optimum conditions.

The optimum condition is defined by studying the main effects of each of the factors. The main effects indicate the general trend of the influence of the factors. Knowing the characteristic, for example, whether higher or lower value produces the preferred results, the levels of the factors which are expected to produce the best results can be predicted.

Knowing the contribution of individual factors is key to deciding the nature of control to be established on a production process. The analysis of variance (ANOVA) is a statistical treatment most commonly applied to the results of the experiment to determine the percent contribution of each factor. Study of the ANOVA table for a given analysis helps to determine which of the factors need control and which do not.[4]

Once the optimum condition is determined, it is usually a good practice to run a confirmation experiment. It is possible to estimate performance at the optimum condition from the results of experiments conducted at non-optimum conditions. It should be noted that the optimum condition may not necessarily be among the many experiments already carried out, as the OA represents only a small fraction of all the possibilities.[33]

Taguchi suggests two different routes to carry out the complete analysis. First, the standard approach, where the results of a single run, or the average of repetitive runs, are processed through main effect and ANOVA analyses for the percent contribution of each factor. The second approach, is to use signal to noise ratio (S/N) for the same steps in the analysis. S/N analysis determines the most robust set of operating conditions from variations within the results.[38]

2.5.8.1 Signal-to-Noise Ratio

Originally, the S/N ratio was an electrical engineering concept defined as the ratio of a signal power to the noise power corrupting the signal. Taguchi expands this concept to the system design area The philosophy of the Taguchi methods stresses that any engineered system is a man-made system, which employs energy transformation to convert input signal(s) into a specific intended function[38]. The signal to noise ratio helps to determine the robustness of the experiment. This concept of signal to noise ratio concept was adapted by Dr. Genichi Taguchi to evaluate the quality of manufacturing processes. Taguchi suggests the "transformation of the repetition output data in a trail into a consolidated single value called the S/N ratio". Here, the 'signal' represents the desirable value and the 'noise' represents the undesirable value and signal to noise ratio expresses the scatter around the desired value. The larger the ratio, the smaller will be the scatter[40] The S/N ratio is quoted in dBi units and it can be defined as:[41]

$$\eta=-10 \log (M.S.D) \qquad \text{Eq.(2.3)}$$

where M.S.D. is the mean-square deviation for the output characteristic. The S/N ratio characteristics can be divided into three stages: the nominal-the better, the smaller-the better, and the larger-the-better when the quality characteristics are continuous for engineering analysis .

2.5.8.1.1 Larger the better [4]

$$\eta_L = -10 \log_{10}\left(\frac{1}{n}\sum \frac{1}{y_i^2}\right) \qquad \text{Eq.(2.4)}$$

Where n = number of replications y_i = observed response value where i = 1, 2,...n; This type of ratio is used when there is no predetermined value for the target and the larger the value of the characteristic, the better the product. Typical examples of its applicability are those cases where the quality characteristic is related to strength of material, length of service life, or fuel efficiency.

2.5.8.1.2 Smaller the better[4]

$$\eta_S = -10 \log_{10}\left(\frac{\sum y_i^2}{n}\right) \qquad \text{Eq.(2.5)}$$

This type of ratio is used when there is a non negative characteristic with an ideal value equal to zero. Typical example of its applicability are those situations where the quality characteristics is related to wear, shrinkage or deterioration

2.5.8.1.3 Nominal-the-best[4]

$$\eta_T = 10 \log_{10}\left(\frac{\overline{Y^2}}{S^2}\right) \qquad \text{Eq.(2.6)}$$

This type of ratio is used when nominal size or characteristic is preferred. Typical example of its applicability are situations where the quality characteristic is related to a dimension clearance ,weight or viscosity and deviations in both directions from the specified target are undesirable.

2.5.8.2 ANOVA

Taguchi replaces the full factorial experiment with a lean, less expensive, faster, partial factorial experiment. Taguchi's design for the partial factorial experiment is based on specially developed OAs. Since the partial experiment is only a sample of the full experiment, the analysis of the partial experiment must include analysis of the confidence that can be placed in the results. A standard technique called Analysis of Variance (ANOVA) is used to provide a measure of confidence. The technique does not directly analyze the data, but rather determines the variability or variance of the data[30]

This method was developed by Sir Ronald fisher in 1930 as a way to interpret the results from agricultural experiments. ANOVA is not a complicated method and has lot of mathematical beauty associated with it. ANOVA is a computational technique to estimate quantitatively the relative contribution which each controlled parameter makes on the overall measured response and is expressed as a percentage. Thus information about how significant the effect of each controlled parameter is on the experimental results can be obtained. [38]

The ANOVA can be done with the raw data or with the S/N data. The ANOVA based on the raw data signifies the factors which affect the average response rather than reducing the variation. But ANOVA based on the S/N data takes into account both these aspects and so it was used here.[33]

2.5.8.2.1 Quantities Used In ANOVA Calculations

2.5.8.2.1.1 Total Number of Trials

In an experiment designed to determine the effect of factor A on response Y, the factor is said to be tested at L levels. Assume n_1 repetitions of each trial that includes A_1. Similarly at level A_2 the trial is to be repeated n_2 times, the total number of trials is the sum of the number of trials at each level and can be represented by:[33]

$$n=n_1+n_2+n_3+\ldots..+n_L \qquad \text{Eq. (2.7)}$$

2.5.8.2.1.2 Degrees of Freedom (DOF)

DOF is an important and useful concept that is difficult to define. It is a measure of the amount of information that can be uniquely determined from a given set of data. DOF for data concerning a factor equals one less than the number of levels.[4] For a factor A with four levels, A_1 data can be compared with A_2, A_3, and A_4 and not with itself. Therefore a four level factor has 3 DOF. Similarly and L_4 OA with three columns representing 2 level factors, has 3 DOF. Figure 2.11 is an illustration of an L_4 OA and its DOF.

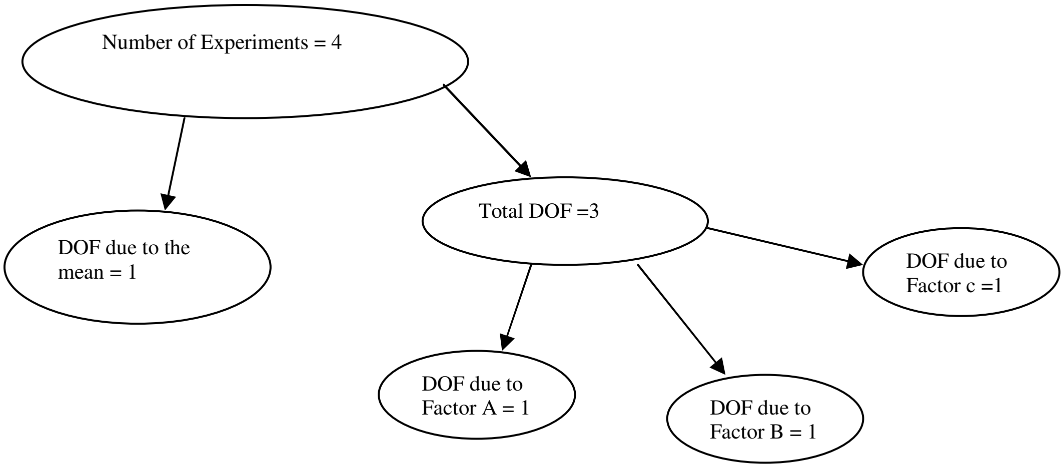


Figure 2.11: DOF in L_4 Analysis[33]

The concept of DOF can be extended to the experiment. An experiment with n trials and r repetitions has n x r trial runs. The total DOF becomes:[33]

$$f_T = n \times r - 1 \qquad Eq.(\ 2.8)$$

Similarly, the DOF for a sum of squares term is equal to the number of terms used to compute to sum of squares and the DOF of the error term f_e is given by:[33]

$$fe = f_T - f_A - f_B - f_C \qquad Eq.\ (2.9)$$

2.5.8.2.1.3 Sum of Squares

Since the purpose of the analysis of variance (ANOVA) is to investigate which process parameters significantly affect the quality characteristic? This is accomplished by separating the total variability of the multi-response signal-to-noise ratios, which is measured by the sum of the squared deviations from the total mean of the multi-response signal-to- noise ratio, into contributions by each of the process parameter and the error.

First, the total sum of the squared deviations SS_T from the total mean of the multi-response signal-to-noise ratio η_m can be calculated as:[19]

$$SS_{T} = \sum_{j=1}^{p} (\eta_j - \eta_m)^2 \qquad Eq.(\ 2.10)$$

Where *p* is the number of experiments in the orthogonal array and η_j is the mean of the multi-response signal-to-noise ratio for the j-th experiment.

The total sum of the squared deviations SS_T is decomposed into two sources: the sum of the squared deviations SS_j due to each process parameter and the sum of the squared error

SS_e

2.5.8.2.1.4 Mean Square

The mean square is calculated by the following formula [33]

$$MS_j = SS_j / f_j \qquad \text{Eq.(2.11)}$$

Where SS_j is the sum of square and f_j is the number of degree of freedom for the factor j

2.5.8.2.1.5 Variance Ratio

The variance ratio, commonly called the F statistic, is the ratio of variance due to the effect of a factor and variance due to the error term for the factor j [33]

$$F = MS_j / MS_{error} \qquad \text{Eq. (2.12)}$$

2.5.8.2.1.6 Percent Contribution

The percent contribution for any factor is obtained by dividing the sum of squares for that individual factor by SS_T and multiplying the result by 100. The percent contribution is denoted by P and can be calculated using the following expressions [33]

$$PC(\%) = (SS_j / SS_T) x100 \qquad \text{Eq.(2.13)}$$

.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Design of Experiment

As discussed earlier the classical experimental design methods are too complex, time consuming and not easy to use. A large number of experiments have to be carried out when the number of process parameters is more. To solve this problem, Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with minimum number of experiments.

3.1.1 Selection of Base Metal

Selection of base metals was basically governed by project design requirements. The base metals were selected keeping in view the strength requirements, weight considerations, resistance to corrosion as well as welding properties. Following is a brief review of the base metal property considerations.[42]

1) HSLA steels developed recently to meet certain demands in critical applications represent a classic example of progress brought about by a good understanding of the structure-property correlations in materials. These steels are mostly low in carbon and are alloyed further to a complex chemistry in order to achieve desired qualities such as refined grain size, increased hardenability etc. Weldability is an important consideration in the selection of such steels for a given application. 15CDV6 is one HSLA steel widely used by Aeronautics and Space Research applications.

2) 15CDV6 steel is remarkably suitable for every welding process, whether oxyacetylene, electric, arc, resistance, electron beam or laser.

3) No preheating is needed to a thickness of 10 mm, and welding in the treated state is just as easy as for annealed metals. After welding, there is no excessive hardening of the cord requiring stress-relief treatment.

4) Indeed, the presence of molybdenum and vanadium means that the annealing effect near the cord, affecting the mechanical strength of steel welded assemblies,

is almost insensitive when 15CDV6 is used. The strength of the treated metal is maintained intact within the cord and around it, so that assemblies with consistent strength exceeding 1,000 MPa can be obtained without any heat treatment. This unique property is confirmed by the thousands of rolled and welded power plants envelopes that have been produced in which the welded generating line is put through the same stresses as the base metal.

5) One major advantage of 15CDV6 steel is that it can be assembled, by welding, with other grades of steel.

3.1.2 Composition of Base Metal

The following table presents the nominal chemical composition of the base metal, [43]

Table 3.1: Composition of Base Metal

Elements	C	Si	Mn	P	S	Cr	Mo	Ni	V
Min	0.12	-	0.8	-	-	1.25	0.80	-	0.20
Max	0.18	0.20	1.10	0.020	0.015	1.50	1.00	-	0.30

3.1.3 Selection of control factors, their levels, and quality characteristics (or responses)

From the previous work done[12,44,45] the most important process parameter in GTAW are arc current arc voltage torch traveling speed and wire feed speed so the control factors (or input parameters) taken are the Arc Voltage (10 – 14 V), Arc Current (80 – 120A), Wire feed speed (3.5 – 5.5mm/sec), Torch Traveling speed (0.9 –1.5 mm/sec) m). The numerical values of factors at different levels are shown in Table3.2. An exhaustive pilot experimentation is done to decide the parameter range. The quality characteristics measured are Tensile strength and Heat Input. The initial setting of parameters is:

Table 3.2: Control Factors and Their Levels

Symbol	Factor	Units	Levels		
			1	2	3
A	Torch Traveling Speed	mm/sec	0.9	1.5	
B	Arc voltage	V	10	12	14
C	Wire Feed Speed	mm/sec	3.5	4.5	5.5
D	Arc current	A	80	100	120

3.1.4 Determination of limiting values for control parameters

The limiting values for the control parameters were determined by varying the values for one parameter while keeping the other three constant.

1) As the current is decreased (the other three parameters i.e. arc voltage, torch travel speed and wire feed speed being kept constant), low values of current will result in insufficient melting of base metal, filler and therefore poor joint characteristics. On the other hand high value of current will result in excessive heat input. So too wide bead, burn through and other defects such as under cut will be observed.
2) If the voltage is decreased to a very low value, (the other three parameters i.e. arc current, torch travel speed and wire feed speed being kept constant) very small arc will be produced. So the tungsten might touch the molten metal which will result in tungsten inclusion etc. on the other hand too high voltage will result in too large arc, as a result arc becomes unstable which lead to defects
3) A high value of torch travel speed (the other three parameters i.e. arc current, arc voltage and wire feed speed being kept constant) will result in decrease of heat input per unit length, this will result in sufficient melting of base metal and filler. On the other hand very low value of torch travel speed will result in high value of heat input per unit length which will cover very wide heat affected zone (HAZ), increase width of weld bead and weld defects such as burn through, excessive

penetration etc will be observed.

4) A high value of wire feed speed (the other three parameters i.e. arc current, arc voltage and torch travel speed being kept constant) will result insufficient weld metal deposition, which will cause under filling of weld joint .on the other hand if it is too high the result will be in overfilling of weld joint leading to excessive reinforcement of weld bead.

3.1.5 Selection of Orthogonal array

To select an appropriate orthogonal array for experiments, the total degree of freedom needs to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, a two-level process parameter counts for one degree of freedom. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In the present study, the interaction between the welding parameters is neglected, because considering interaction means selecting larger orthogonal array and as a result number of experiments increases. So keeping in view the desired outcome of the project(just to analyze the main effects) and its cost limitations, interaction is neglected.

once the degree of freedom are known the next step is to select an appropriate orthogonal array to fit the specific task The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters, therefore in this study, an L_{18} orthogonal array with 3 columns and 18 rows was used. This array has 17 degrees of freedom and it can handle 3 level process parameters. Eighteen experiments were required to study the welding parameters using L_{18} orthogonal array. The experimental layout for the welding process parameters using the L_{18} orthogonal array is shown in Table 3.3

Table 3.3: L18 Orthogonal Array (OA)

Experiment No	Factor Level			
	Torch Traveling Speed	Arc voltage	Wire Feed Speed	Arc Current
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

3.1.6 Nominal Mechanical Properties of Base Metal

The nominal mechanical properties of the base metal are presented in the following table, [43]

Table 3.4: Nominal Properties of Base Metal

Rm >700Mpa	980 < Rm< 1180	1080 < Rm < 1250
Annealed	Quenched in air	Quenched in oil

3.1.7 Selection of Welding Consumables

3.1.8 Composition of Filler

Following is the chemical composition of filler

Table 3.5: Composition of Filler

elements	C	Mn	Cr	Mo	others
	0.11	1.0	1.4	0.9	V=0.25

3.1.9 Composition of Shielding Gases

Argon gas was used for shielding purposes with a purity of 99.99%.

3.1.10 Preparation of Specimen for Welding

Specimen were selected from the base metal sheet as per following dimensions,

Dimension of specimen = 250 mm x 150 mm

Thickness = 2.5 mm

3.1.11 Selection of Weld Joint

Joints were prepared using milling operation to avoid effects of joint variation on properties of welded specimen. Due to the low thickness of the base metal, a square butt joint was selected with no root gap.

3.1.12 Welding Equipment Used

Experiments were carried out using Semi-Automatic Mechanized Welding Equipment. The equipment was equipped with matching wire feed system (double roll mechanism), and arc length control system (Jet Line) to minimize variation of welding parameters (such as arc voltage and torch speed) due to slight variations in component geometry, inaccuracies in welding tooling etc.

3.2 Conduct of Experiments

Prior to welding, the base metal sheets were wire brushed and cleaned with emery paper.

Degreasing was carried out using acetone. The sheets to be welded were kept on copper backing bar and sides were clamped to maintain the alignment and gap. Purging is provided at the bottom of the sheets. The same argon gas is used for shielding as well as purging. An automatic TIG welding machine has been employed for conducting the welding experiments. The weld joint is completed in single pass.

3.2.1 Preparation of Specimen for Mechanical Testing

Specimens for mechanical testing were prepared using standard milling operations. Strict control of dimensions was maintained through standard quality control procedures for dimensional tolerances, special care being taken to avoid any defects that could affect the quality of testing results.

3.2.2 Layout of Test Specimen

Specimens for testing were removed from welded specimen, keeping in view the requirements of relevant ASTME8 standards. Typical geometrical layout for test specimen is as shown in the figure below.

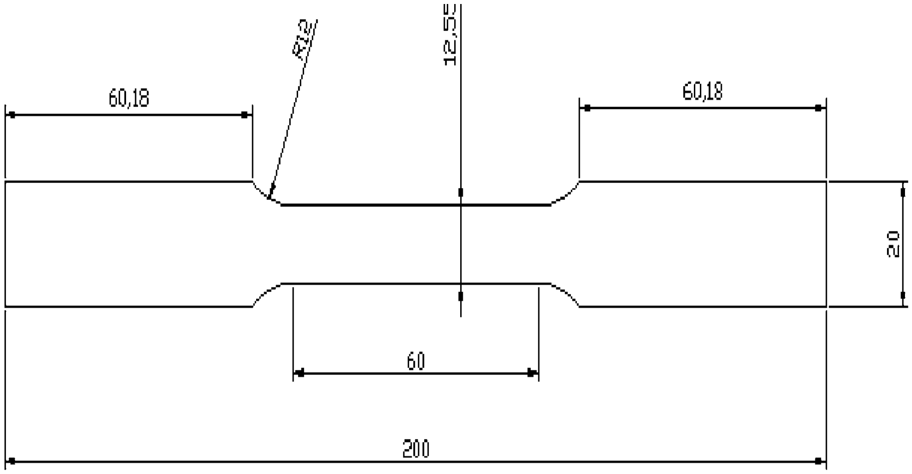


Figure 3.1: Tensile Test Specimen

3.2.3 Testing Equipment Used

Mechanical testing was carried out using Universal Testing Machine from Tinus Olsen..

Figure 3.2: Universal Testing Machine

3.2.4 Record the quality characteristics (i.e Tensile strength and Heat Input)

- Specimens for tensile testing were taken at the middle of all the joints and machined to ASTM E8 standards. The configuration of specimen used under tensile testing is shown in Fig:3.1. Tensile test was conducted using a computer-controlled universal testing machine with a cross head speed of 0.5 mm/min. All the welded specimens were failed in the weld region. The ultimate tensile strength of the weld joint is the strength of the weld.

- Heat input was calculated using the following relationship,

$$\text{Heat Input (Joules / mm)} = V \times A / TTS \qquad \text{Eq.(3.1)}$$

Where,

V = Voltage (volts)

A = Current (Amps)

TTS = Torch Travel Speed (mm/s)

Where the measurement of Voltage, Current and Torch Travel Speed (Welding Speed) was carried out using calibrated meters installed on the welding machine.

CHAPTER 4

RESULT AND ANALYSIS

4.1 Experimental Results Using L_{18} OA

Table 4.1: Experimental Results Using L18 OA

Experiment No	Tensile Strength MPa	Heat Input Joules/mm
1	1030	888.8889
2	1066	1111.111
3	1031	1333.333
4	1066	1066.667
5	1075	1333.333
6	1072	1600
7	1066	1555.556
8	1067	1866.667
9	1064	1244.444
10	1005	800
11	1060	533.3333
12	1025	666.6667
13	1055	800
14	1040	960
15	1050	640
16	1002	1120
17	1025	746.6667
18	1029	933.3333

4.2 Analysis

4.2.1 Computation of Quality Loss for Each Quality Characteristic

In Taguchi method [46, 47], a quality loss or mean square deviation (MSD) function is used to calculate the deviation between the experimental value and the desired value. The MSD is different for different types of problems. In present case the tensile strength is larger the better type and Heat Input is Smaller the better type .so for Tensile strength (larger the better type) quality loss will be calculated as

$$MSD = (1/y_1^2 + 1/y_2^2 + 1/y_3^2...)/n \qquad Eq.(4.1)$$

And quality loss for Heat Input (smaller the better type) will be calculated as

$$MSD = (y_1^2 + y_2^2 + y_3^2 + ...)/n \qquad Eq.(4.2)$$

Where $y_1, y_2, y_3... y_n$ are the results of experiments (responses) and n is the number of repetitions of yi

Table 4.2: Quality loss For Tensile Strength and Heat Input

Experiment No	Quality Loss(dB)	
	Tensile strength (MPa)	Heat Input (Joules/mm)
1	9.42596×10^{-07}	790123.5
2	8.80006×10^{-07}	1234568
3	9.40768×10^{-07}	1777778
4	8.80006×10^{-07}	1137778
5	8.65333×10^{-07}	1777778
6	8.70183×10^{-07}	2560000
7	8.80006×10^{-07}	2419753
8	8.78357×10^{-07}	3484444
9	8.83317×10^{-07}	1548642
10	9.90075×10^{-07}	640000
11	8.89996×10^{-07}	284444.4
12	9.51814×10^{-07}	444444.4
13	8.98452×10^{-07}	640000
14	9.24556×10^{-07}	921600
15	9.07029×10^{-07}	409600
16	9.96012×10^{-07}	1254400
17	9.51814×10^{-07}	557511.1
18	9.44429×10^{-07}	871111.1

4.2.2 Computation of normalized quality loss for each quality characteristic

The engineering units for describing the tensile strength and heat input are different. To consider the two quality characteristics in the Taguchi method, the quality loss corresponding to the tensile strength and heat input are first normalized.

Normalization is a transformation performed on a single data input to distribute the data evenly and scale it into an acceptable range for further analysis Several methods have been developed for solving a multi-response optimization problem. In this study, a weighting method is used for the optimization of a GTAW welding parameter optimization with multiple performance characteristics. Usually, the weights are determined purely based on engineering judgment [48], but it still remains difficult to determine and define a definite weight for each response in a real case.

Let L_{ij} be the quality loss for the i_{th} quality characteristic at the j_{th} trial condition or run in the experimental design matrix. Since each of the quality characteristic has different unit of measurements, it is important to normalize the quality loss [32]. The normalized quality loss can be computed using

$$Z_{ij} = L_{ij} / L_i^* \qquad \textit{Eq. (}4.3)$$

Where, Z_{ij} = normalized quality loss

Li^* = maximum quality loss for the i^{th} quality characteristic among all the experimental runs. Therefore, Z_{ij} varies from a minimum of zero to a maximum of 1. The computed normalized quality loss for tensile strength and heat input is given in Table 4.3.

Table 4.3: Normalized quality loss For Tensile Strength and Heat Input

Experiment No	Normalized quality loss	
	Tensile Strength	Heat Input
1	0.94637	0.226757
2	0.883529	0.354308
3	0.944535	0.510204
4	0.883529	0.326531
5	0.868797	0.510204
6	0.873667	0.734694
7	0.883529	0.694444
8	0.881874	1
9	0.886854	0.444444
10	0.994039	0.183673
11	0.89356	0.081633
12	0.955625	0.127551
13	0.90205	0.183673
14	0.928258	0.26449
15	0.910661	0.117551
16	1	0.36
17	0.955625	0.16
18	0.94821	0.25

4.2.3 Computation of Total normalized quality loss

For computing the Total normalized quality loss corresponding to each trial condition, we must assign a weighting factor for each quality characteristic considered in the optimization process. If w_i represents the weighting factor for the i_{th} quality characteristic, k is the number of quality characteristics and Z_{ij} is normalized quality loss associated with the ith quality characteristic at the j_{th} trial condition, then Y_j can be computed using:[49]

$$Y_j = \sum_{i=1}^{k} w_i Z_{ij} \qquad Eq.(\ 4.4)$$

In present case, $k = 2$, and assuming unequal weights i.e. $w_1 = 0.8$ for tensile strength, and $w_2 = 0.2$ for heat input. The total normalized quality loss in each experimental run is shown in Table 4.4.

4.2.4 Computation of multiple S/N ratio (MSNR)

After the total normalized quality loss (Yj) corresponding to each trial condition has been calculated, the next step is to compute the multiple S/N ratio at each design point. This is given by:[49]

$$\eta_j = -10 \log_{10} (Yj) \qquad Eq.(\ 4.5)$$

The multiple S/N ratios along with total normalized S/N ratio in each trial condition is shown in Table 4.4.

In single quality optimization using Taguchi methodology, sections 4.2.2 and 4.2.3 are omitted, and in place of a multiple S/N ratio, separate S/N ratios corresponding to each quality characteristics is computed where the Yj are the S/N ratio values of different quality characteristics. Other steps are same as in multi-objective optimization

Table 4.4: Total Normalized quality loss (TNQL) And Multiple S/N Ratio (MSNR)

Experiment No	TNQL	Multiple S/N Ratio (MSNR)
1	0.802448	0.955834
2	0.777685	1.091961
3	0.857669	0.666803
4	0.77213	1.123097
5	0.797079	0.984988
6	0.845872	0.726952
7	0.845712	0.727773
8	0.905499	0.431119
9	0.798372	0.977946
10	0.831966	0.798946
11	0.731175	1.35979
12	0.790011	1.023671
13	0.758375	1.201163
14	0.795504	0.993574
15	0.752039	1.237595
16	0.872	0.594835
17	0.7965	0.98814
18	0.808568	0.922833
Mean MSNR(dB)		0.933723

4.2.5 Determination of factor effects and optimal settings

Next step is to determine the average effect of each factor on multiple quality characteristic at different levels. This is equal to, the sum of all S/N ratios corresponding to a factor at particular level divided by the number of repetition of factor level. The factor levels corresponding to maximum average effect are selected as optimum level. The average factor effect has been shown in Table 4.5. The optimum setting of parameters is $A_2B_2C_2D_1$

Table 4.5: Effect of Factor Level on MSNR

Factors	Mean MSNR		
	Level 1	Level 2	Level 3
Torch Traveling Speed	0.854053	1.013394*	
Arc Voltage	0.982834	1.044561*	0.773774
Wire Feed Speed	0.900275	0.974929*	0.925967
Arc Current	1.107067*	0.992065	0.702038

* Optimum Parameter Level

4.2.6 Response Graphs

The response graphs exhibit a pictorial view of variation of each parameter and describe what the effect on the system performance would be, when a parameter shifts from one level to another. Figure 4.1 shows the multi response signal-to-noise graph and the dash line indicated in Figure 4.1 is the value of the total mean of the multi response signal-to-noise ratio. The larger the multi-response signal-to-noise ratio, the smaller the variance of quality characteristics around the desired value. However, the relative importance among the welding parameters for the multiple quality characteristics still needs to be known so that the optimal combinations of the welding parameter levels can be determined more accurately.

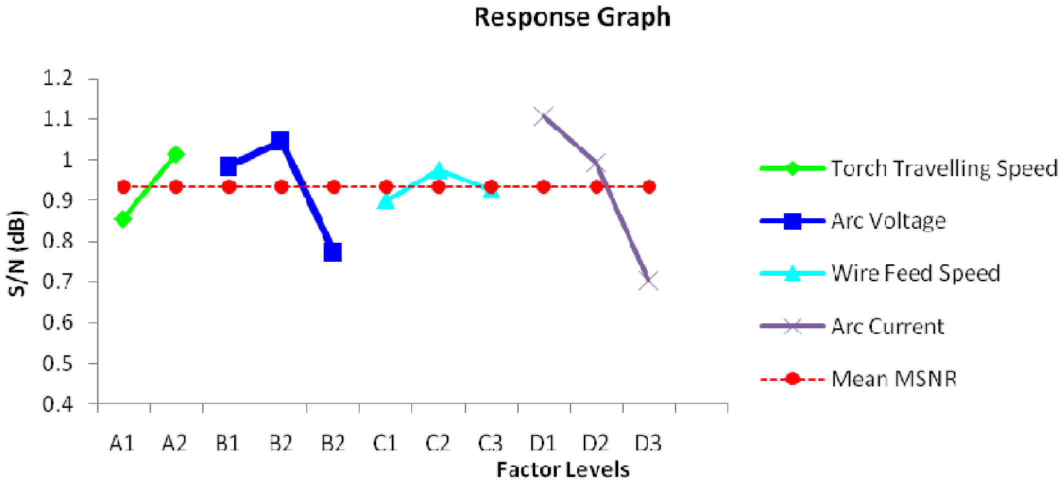


Figure 4.1: Effect of Factor Level on MSNR

4.2.7 ANOVA

The main objective of ANOVA is to extract from the results how much variation each factor causes relative to the variation observed in the result. For a set of results the total variation can be calculated by adding deviations of the individual data from the mean value. To assure that all deviations are counted, the individual deviations are squared, which forces all values to be positive

Table 4.6: Result of Analysis of Variance (ANOVA) for Welding Performance

Symbol	Welding Parameter	Degree of Freedom	Sum of Square	Mean Square	F	Contribution Percent
A	Torch Traveling Speed	1	0.114254	0.114254	15.82864	11.80112
B	Arc Voltage	2	0.241684	0.120842	16.74138	24.96325
C	Wire Feed Speed	2	0.017261	0.008631	1.195675	1.782883
D	Arc Current	2	0.522779	0.261389	36.21274	53.99719
ERROR		10	0.072182	0.007218		7.455553
TOTAL		17	0.968159	0.056951		100

The percent contribution for the error is 7.4% which is satisfactory. If the percent contribution for the error is a high value say 40% or more, then some important factors were omitted, conditions were not precisely controlled, or measurement error was excessive [30]

4.3 Confirmation test

Conducting a verification experiment is a crucial final step of a robust design. Once the optimal level of the process parameters is selected; the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the process parameters. The predicted value of multiple S/N ratio at optimum level is calculated by the following formula [49]

$$\eta_o = \eta_m + \sum_{i=1}^{q} (\eta_i - \eta_m) \qquad Eq.(4.6)$$

Where η_m is the total mean of the multi response signal-to-noise ratio, η_i is the mean of the multi-response signal-to noise ratio at the optimal level, and q is the number of the process parameters that significantly affect the multiple quality characteristics.

Based on Equation 4.6, the estimated multi-response signal-to-noise ratio using the optimal welding parameters can then be obtained. Table 4.7 shows the results of the confirmation experiment using the optimal welding parameters. There is good agreement between the predicted welding performance and actual welding performance. The increase of the multi response signal-to-noise ratio from the initial welding parameters to the optimal welding parameters is 0.369dB.

Table 4.7: Results of Confirmation Experiment

	Initial setting	Optimum values	
		Prediction	Experiment
Level	A1B1C1D1	A2B2C2D1	A2B2C2D1
Tensile Strength	1030		1061
Heat Input	888.88		640
MSNR(dB)	0.955834	1.29757593	1.32525836
			0.36942478

CHAPTER 5

DISCUSSION

Following is a brief discussion of the results obtained and data gathered during the course of the experimental work.

Before making an attempt to review the results of experimental work and analysis procedures (ANOVA) used, it is important first that a brief consideration be given to various factors affecting the results during the course of this investigation. This will serve to provide a better explanation and understanding of the results obtained in this investigation.

5.1 Design of Experiments

It is important to remember that prime factor governing the selection of optimization procedures is the efficiency of the optimization process rather than the accuracy alone. The efficiency of the optimization procedure is determined by a combination of factors such as number of experiments (which in turn determine both the required time and cost of the optimization) as well as level of optimization achieved. Thus a further optimization of results might be possible but only at the expense of times and costs involved. Taguchi method of optimization was selected keeping in view these considerations. A further optimization can be obtained either by simply increasing the number of levels (which will result in a better sweeping of design space), or by repeating the Taguchi optimization around the determined optimal values.

5.2 Experimental Work

Welded fabrication is one of the most difficult manufacturing processes to control. This is due not only to the nature of the control parameters but also due to factors which are often beyond the control of investigators. Obtained results are often affected by the environment as well as quality of welding power sources used and may not by completely repeatable. The results can also vary from one power source to other. Also, the results can be affected by accuracy of fabrication involved in specimen. The joint fitup and alignment is often not completely repeatable and may affect the obtained results.

Every effort has been made to minimize the effect of such variations and increase the repeatability of the process. Nevertheless, it is important to keep in mind the variations in quality attributes due to un-controllable causes.

5.3 Evaluation of Properties

Another source of variation is the evaluation of target properties. The observed properties are affected not only by the manufacturing process, but also the way the properties have been evaluated during investigation. This include the selection of welded specimen, location where the test specimen have been obtained from, preparation of specimen for testing, test machines and mechanisms used, as well as selection of testing parameters.

Once again every effort has been made to minimize the variations in quality attributes due to these causes.

5.4 Analysis of Results

Analysis of results indicate that the Arc current , Arc voltage and Torch Traveling speed have the most profound effect on the results, whereas wire feed speed has the least effect on the results of welding process. The results can have a profound effect on the control of manufacturing process involving welding.

A close control of welding process will require a closer control of current and voltage and travel speed. A change in any of these factors will result in a direct variation in the results of the process. However, the parameters having least affect on the manufacturing process have also been identified. For example, wire feed speed having least effect on the weld properties indicate that this parameters can be varied comfortably without having any profound effect on the resultant properties.

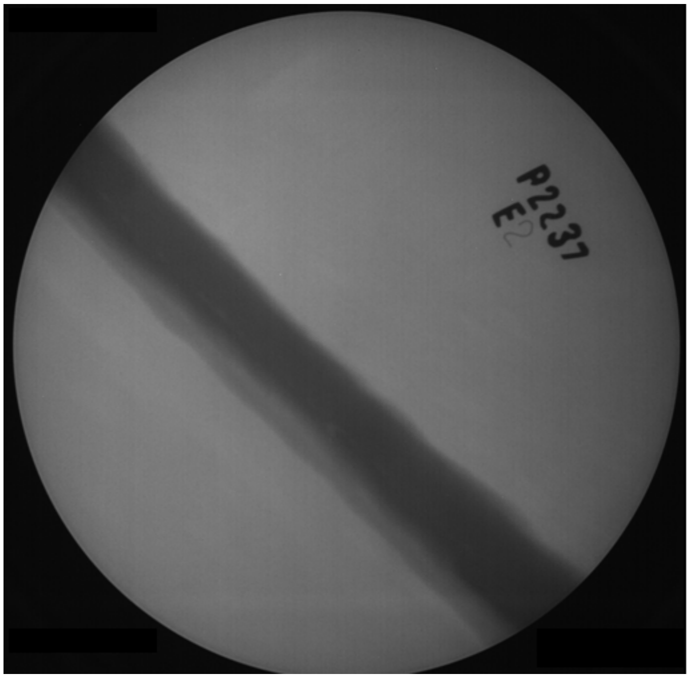
CONCLUSIONS

Following is a brief of conclusions drawn from the research investigation,

1. Taguchi method is successfully employed to optimize the multiple quality characteristics.
2. A significant increase in S/N ratio (0.369dB) has been registered at optimum parameter setting in the present experimental investigation.
3. Both the quality characteristics (heat Input and tensile strength) have been considerably improved as compared to initial parameter settings of the experiment
4. The optimum parameter values in the present operating conditions are: torch traveling speed - 1.5mm/sec, wire feed speed - 4.5mm/sec, arc voltage - 12V and arc current- 80A.
5. The percentage contribution of factors in increasing order is: arc current-53.99% , arc voltage-24.90%,torch traveling speed-11.80%,wire feed speed-1.78%

A review of the manufacturing process after implementation of optimized parameters indicated the expected improvements in the overall characteristics of the process. Before implementation of the optimization process, satisfactory welds were being produced. However more important is the fact that defects were frequently encountered which required repair and rework. This meant a loss both in terms of time (product delivery schedules), cost and quality of final products. Inconsistency in various quality characteristics presented a real challenge.

Significant improvement in the manufacturing process was observed in the form of reduced weld defects(as shown in fig 6.1), thus reducing the requirements for repair and rework. The overall consistency in quality attributes was evident with the standardization of welding procedures across the production shop floor.



[redacted]

[redacted]

[redacted]

Figure 6.1: Weld Obtained after the Implementation of Optimized Parameters

RECOMMENDATIONS

Through out the course of the research, every effort was made to provide the accurate and best available solution to the optimization problem. However, the research activities could not be extended to all possible areas mostly due to the constraints imposed by factors beyond the control of research team such as availability of materials as well as availability of production machines and manpower for research work.

Following are some of the areas which might attract interest of future researchers and bring upon further improvement in the manufacturing process.

1) Implementation of pulsed GTAW techniques
2) Consideration of interactions between various factors
3) Introduction of additional factors such as pulsing characteristics and additional quality attributes such as bead geometry for simultaneous optimization.

REFERENCES

1. Bernard Mannion and Jack Heinzman III “**Determining parameters for GTAW”** *published in the July/August 1999 issue of Practical Welding Today*
2. Bilal Ahmed, “ **Distortion Response of Synchronized Tandem Wire Gas Metal Arc Welding**”, *School of Industrial and Manufacturing Science Cranfield University Academic Year 2005-2006*
3. May 2002,“**Welding-Related Expenditures, Investment and Productivity Measurement in U.S. Manufacturing, Construction and Mining Industries**”, *Bureau of Industry and Security – U.S. Department of Commerce*, Available www.bisc.doc.gov (Accessed 19th Jan, 2009)
4. Alberto Garcia - Diaz And Don T. Phillips, “**Principles Of Experimental Design And Analysis”,** *published by Chapman and Hall ,1994.*
5. ASM Handbook , “**Welding, Brazing and soldering**”, *published in 1993 as volume 6 of the ASM (American Society of Metals) handbook.*
6. Lincoln Electric (1994), “**The Procedure Handbook of Arc Welding”.**
7. Jeffus, Larry (2002), “**Welding: Principles and Applications”.**
8. AWS(2000) , “**Welding Handbook**”, *Eighth Edition Volume 2.*
9. Paulraj Sathiya, S.Arvindan, A.Noorul Haq**, “Optimization For Friction Welding Parameters With Multiple Performance Characteristics”**, *Int J Mech Mater Des(2006).*
10. Paul E. Black, **“U.S. National Institute of Standards and Technology”**, 17 December 2004. (accessed on 2 jan 2009) Available from: http://www.itl.nist.gov/div897/sqg/dads/HTML/simulatedAnnealing.html.
11. Roytman Alexey, **“Simulated Annealing Method”**, *Ben-Gurion University of the Negev, Israel, 1998.*
12. Y. S. Tarng, J. L. Wu, S. S. Yeh and S. C. Juang, **“Intelligent Modeling And Optimization Of The Gas Tungsten Arc Welding Process”,** *Int. J. Mach. Tools Manuf.*

13. Mr. Pikid Duangmala, “**Optimization of Gas Metal Arc Welding Parameters for Steel ST 37 Using Response Surface Method**. *International Journal of Advance Manufacturing Technology (2002).*
14. Hsien-Yu Tseng, “**Welding parameters optimization for economic design using neural approximation and genetic algorithm”,** *International Journal of Advance Manufacturing Technology (2006).*
15. D. S. Correia, C. V. Gonçalves, Sebastião S. C. Junior, V. A. Ferraresi, “**GMAW Welding Optimization Using Genetic Algorithms”,** *J .of the Braz Soc. of Mech. Sci & Eng*.
16. http://www.ee.iitb.ac.in/~apte/CV_PRA_TAGUCHI_INTRO.htm accessed on 3 jan 2009
17. Zhang, Y.M., Kovaceive, R., Li, L.:, “**Characterization and real time measurement of geometrical appearance of the weld pool”,** *Int. J. Mach. Tools Manuf. 36(7), 799–816 (1996)*
18. Bendell, A., Disney, J., Pridmore, W.A.:, “**Taguchi Methods: Applications in World Industry”,** *IFS Publication, UK (1989)*
19. Y. S. Tarng and W. H. Yang, **“Application of the Taguchi Method to the Optimization of the Submerged Arc Welding Process”,** *Journal of Materials and Manufacturing processes(1998).*
20. M.Balasubramanian, V.Jayabalan and V.Balasubramanian **“Process Parameter Optimization Of The Pulsed Current Argon Tungsten Arc Welding Of Titanium Alloy”,** *Journal of Materials Sciences & Technology.*
21. Murugan, N., R. S. Parmar, and S. K. Sud, “**Effect of Submerged Arc Welding Process Variables on Dilution and Bead Geometry in Single Wire Surfacing**”, *Journal of Materials Processing Technology, Vo!.37, pp.767-780, (1993).*
22. Yang, L. J., M. J. Bibby, and R. S. Chandel, “**Linear Regression Equations for Modeling the Submerged Arc Welding Process”,** *Journal of Materials Processing Technology, Vo1.39, pp.3342, (1993).*
23. Srihari T. and R. S. Parmar, “**Weld Bead Geometry Prediction**”, *Journal of the Institution of Engineers, India, Vo1.76, pp.39-43, (1995).*

24. Tsai, H. L., Y. S. Tarng, and C. M Tseng, **“Optimization of Submerged Arc Welding Process Parameters in Hard facing”**, *International Journal of Advanced Manufacturing Technology, Vo1.l2, pp A02-406, (1996).*
25. G.Taguchi,**“Introduction to Quality Engineering”,** *Asian Productivity Organization, Tokyo, pp.121-148, (1990).*
26. Ross, P. J., **“Taguchi Techniques for Quality Engineering”**, *McGraw-Hill, New York, pp.203-205, (1988)*
27. Peace, G. S., “**Taguchi Methods: A Hand-on Approach”**, *Addison- Wesley, Reading Massachusetts, pp.I-12, (1993).*
28. A Jayant, V Kumar, “ **Prediction of Surface Roughness in CNC Turning Operation using Taguchi Design of Experiments Department of Mechanical Engineering”** , Sant Longowal Institute of Engineering and Technology, Longowal, Punjab Vol 88, March 2008
29. WTEC Hyper-Librarian, **“Design of Experiments, QC and Taguchi Methods”,** *Published: April 1994*
30. Dale H.Besterfield,Carol Besterfield-Michna,Glen H.Besterfield,MaryBesterfield-Sacre,**“Total Quality Management”**, *published by Pearson Education,Inc.Pearson Prentice Hall 2006.*
31. R, Jones & Associates, **“Experimental Design and Taguchi Methods**”, *Texas Instruments, Dallas, TX, 1989*
32. Antony, J., “**Simultaneous optimization of multiple quality characteristics in manufacturing processes using Taguchi’s quality loss function**,” *International Journal of Advance Manufacturing Technology, Vol. 17, pp. 134-138, 2001.*
33. Christopher M. Towle, B.S.E.E, “**Exposure Of Soft Defects In Integrated Circuits Using Taguchi Methods” ,** *Department Of Electrical Engineering Texas Tech University 1999*
34. G. Taguchi, **“Taguchi Methods Design of Experiments”** , *ASI Press, Dearborn, MI, 1993*
35. http://www.qualcost.com/hTagMet.htm accessed on 8 jan 2009
36. R Roy, **“Design of Experiments Using the Taguchi Approach”,** *John Wiley & Sons Inc., New York, 2001*
37. G. Taguchi, S. Chowdhury, S. Taguchi, **“Robust Engineering”**, *McGraw-Hill,*

New York, 2000.

38. Ranjit K. Roy, " **A Primer on the Taguchi Method"** , *Society of Manufacturing Engineers Dearborn, Michigan(1990)*
39. W. Fowlkes, C. Creveling, "**Engineering Methods for Robust Product Design",** *Addison- Wesley Publishing Company, Reading, MA, 1995*
40. S. Shaji, V. Radhakrishnan , "**Analysis of process parameters in surface grinding with graphite as lubricant based on the Taguchi method**" ,*Journal of Materials Processing Technology, Oct (2003).*
41. Hasan Oktem , Tuncay Erzurumlu , Ibrahim Uzman, " **Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part** " , *Materials and Design 28 (2007)*
42. K. Ray, E. S. Dwarakadasa and K. S. Raman**, "Effect Of Porosity And Slag Inclusions On The Fatigue Fracture Behavior Of 15CDV6 Butt Welds" ,** *Journal of Materials Science (1986) .*
43. www.donfoster-racing.fr/materiaux_gb.htm accessed on 2 Mar 2009
44. *I.Uygur,I.Dogan,"***The Effect Of TIG Welding On Microstructure And Mechanical Properties Of A Butt Joined Unalloyed Titanium",** *METALURJIGA 44(2005)2,Pg 119-123*
45. Y. S. Tarng and W. H. Yang, "**Optimization of the Weld Bead Geometry in Gas Tungsten Arc Welding by the Taguchi Method",** *International Journal of Advance Manufacturing Technology (1998.)*
46. Chen, Y. H., Tam, S. C., Chen, W. L. and Zheng, H. Y., **"Application Of Taguchi Method In The Optimization Of Laser Micro-Engraving Of Photomasks"**, *International Journal of Materials & Product Technology, Vol. 11, No. 3/4, pp. 333-344, 1996.*
47. Han, S. R., Park, T. W. and Jeong, Y. D., **"Effects of process variables on the gas penetrated part in gas-assisted injection molding"**, *International Journal of Precision Engineering and Manufacturing, Vol. 7, No. 2, pp. 8-11, 2006.*
48. Tong, L.-I., Su, C.-T., Wang, C.-H., **"The optimization of multi response problems in the taguchi method"**, *Int. J. Qual.Reliab. Manage. 14(4), 367–380 (1997)*

49. Avanish Kumar Dubey, Vinod Yadava1, “ **Simultaneous Optimization of Multiple Quality Characteristics in Laser Beam Cutting Using Taguchi Method**”, *International Journal of Precision Engineering and Manufacturing Vol. 8, No.4, Oct 2007*