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Statistical Analysis for Quality Welding Process: An Aerospace Industry Case Study

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Abstract: The analysis of a Gas Tungsten Arc Welding Process (GTAW) was realized in an aerospace industry for steel heat exchangers, components that have their function in the air conditioning system of an airplane. It was identified the optimal levels and most significant variables for welding process that directly or indirectly influence quality defects. The welding process for heat exchangers has significant quality defects which delays the manufacturing process, as well as increases downtimes in the production area. For this case study, Taguchi's methodology of design of experiments was used considering the characteristics of the process, i.e., low production rate and a large number of variables to be analyzed. Based on the results were identified the optimal levels and most significant variables that influence on quality defects which were rod type on level 1, cleaning unit previous brazing zone on level 1, amperage on level 2, electrode type on level 1 , rod cleaning on level 1. With the recommended conditions, the GTAW defects were diminished by 36%, increasing the level of productivity and decreasing production costs.

Key words: Steel heat exchangers, gas tungsten arc welding, design of experiments, quality control

INTRODUCTION

The company where the experiment was conducted is an aerospace industry located in Mexico, this corporation has design and manufacturing facilities in: United States, Canada, Brazil, China, Mexico, among others. The manufactured aerospace parts are steel heat exchangers and their function is focused on airplane air conditioning system. These aerospace parts are assemblies that go through different welding process such as GTWA and brazing.

Gas Tungsten Arc Welding (GTAW) is one of the most common soldering processes is it requires heat fusion which is generated by an arc between a non-consumable tungsten electrode and the base metal. This process can be used with or without filler metal. Brazing is a joining process where metals are bonded together using a non-ferrous filler metal with a melting (liquids) temperature greater than 450°C (840°F). Filler metals are generally alloys of silver (Ag), aluminum (Al), gold (Au), copper (Cu), cobalt (Co) or nickel (Ni) (Sulzer Metco, 2009).

There are a lot of studies that use statistics tools to solve welding process problems which suggest that the planning phase of a design of experiments is the first real task to reach an objective. Description the stages through design of experiment should be conducted, as: Knowing the problem, define the goals, selecting factors in the experiment, selection of the design of experiments and factor levels, selection sample size and data collection, experimental analysis (Viles *et al*., 2008).

On the other hand, Bisgaard and Pinho (2004) analyzed the design of experiments with Taguchi's methodology to verify the dispersion effects on response variables for an arc welding process. They had sixteen tests with nine factors with an objective of find the best conditions in terms of tensile and elongation.

The steel heat exchangers (in this case study) are welded with GTAW process and present several defects as porosity cracks and leaks that caused production delays and cost increases. The purpose of this study was to identify the optimal levels and most significant variables that influence the appearance of defects in welding such as pores, cracks and incomplete penetration as well as describe some of the stages to define the most important variables considered in welding process.

METHODOLOGY

Experimental design: Taguchi's philosophy determines that the quality of a product should be measured in terms of lowering to a minimum product loss. The Taguchi's methodology establishes three goals:

- Robust designs (insensitive) to the environment for products and processes

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- Product design and development, so that they are robust to variation of components
- Minimization of the variations with respect to a target value (Pulido *et al.*, 2008)

The experimental design was performed as the first stage of the development planning of testing; control instruments potential factors in the process and staff training, in order to define the procedures and activities that will continue to successfully test development. For experiment it was used Taguchi's method with orthogonal array L_8 with seven factors corresponding to eight tests.

Features that will be implemented for experimental design are focused on use in a first phase the Taguchi method with an array L_8, this methodology uses orthogonal arrangements involving all variables suspected to cause a variation in a process but without testing all possible combinations of the same test for different levels as in a full factorial design. This method is considered useful when have very large number of factors, when interactions between them are not a high number and especially when the experimenter has a good knowledge of the process. This methodology also helps to make relatively fewer test runs conventional arrangements saving time and material and human resources, especially in the early stages of experimentation.

Materials and equipment: Aerospace parts are critical assembly units that pass through several welding processes, particularly in GTAW and brazing. The heat exchangers are made of steel and its function is primarily focused on airplane air conditioning system. This type of weld works with a filler material is identified with steel shafts with different diameters depending on the parts to be welded. The heat exchangers are integrated by several components which are subsequently joining them by GTAW. A total of twenty types GTAW joints, are considered as a critical work which requires great welder skills.

Experimental planning: For the experimental plan at an early stage it was decided to work with the staff involved awareness regarding the benefits and scope of design of experiments, since many of the people involved in the pilot phase was not familiar with this topic. One strategy chosen to achieve this goal was to conduct various trainings with all personal involved including information about the application of experimental design to a production process, the meaning of the potential factors in welding process and their level of specification (lower and upper). Table 1 displays detailed information for significant variables.

Welding parameters: GTAW is widely used for welding stainless steel, aluminum, magnesium, copper and reactive materials such as titanium and tantalum. The process is also used to join carbon steels and alloys. The GTAW process is applicable when is required a weld quality. This kind of welding can be used to weld almost all kinds of metals (Campbell, 2011).

In GTAW process there are significant parameters to ensure the quality of the weld beads, so it is important to consider for the experimental tests. The following describes each of the parameters related to GTAW study.

Rod type: The process uses two types of filler material of different composition.

Cooling time: Not currently considered as any specification in welding process, however, the component is made with approximately twenty welds around, so is advisable a minimum cooling time to avoid any internal deformations.

Unit cleaning in pre-brazing area: There are several components in heat exchangers where brazing is applied prior to GTAW. Brazing occasionally tends to slip on the component which could cause a defect. Two types of removers will be evaluated.

Amperage: The rating is determined by each welder. A work instruction includes amperage range which the welder can vary.

Electrode type: The main function of an electrode is to create an electric arc between base material and filler metal which allows the casting of these elements. The welder requires the using of an electrode, for experimental purposes, two types: A 0.09375" and 0.0625" diameter are used.

Rod cleaning: This activity it is mandatory in order to remove any residual contaminants on welds. For experimentation two types of tissues were tested.

Welding sequence: The sequence refers to the order that welder performs weld beads around the heat exchangers. Sequence A and B were used during experimental tests. The difference between two sequences is the order wich components are soldered.

Relative humidity: This is a noise variable, because although it can be measured, is not currently controlled, given the characteristics of the process.

Temperature: Similar to humidity, environment temperature is considered a noise variable. Table 1 shows the significant variables that affect weld quality.

Table 1: Significant variables description with upper and lower limits

Variables	Controlled (C) or noise (N) variable	Unit	Designation	Specification limits Lower	Upper
Type of rod	C	Supplier	V	Type rod # 1	Type rod # 2
Cooling time	C	Minutes	T	5	10
Cleaning unit on previous brazing zone	C	Brush	U	Red tow	Wire brush
Amperage	C	Amperes	A	60	50
Type of electrode	C	Diameter in.	E	0.09375	0.0625
Cleaning rod	C	Supplier	L	Supplier # 1	Supplier # 2
Welding sequence	C	Type	S	A	B
Relative humidity	N				
Temperature	N				

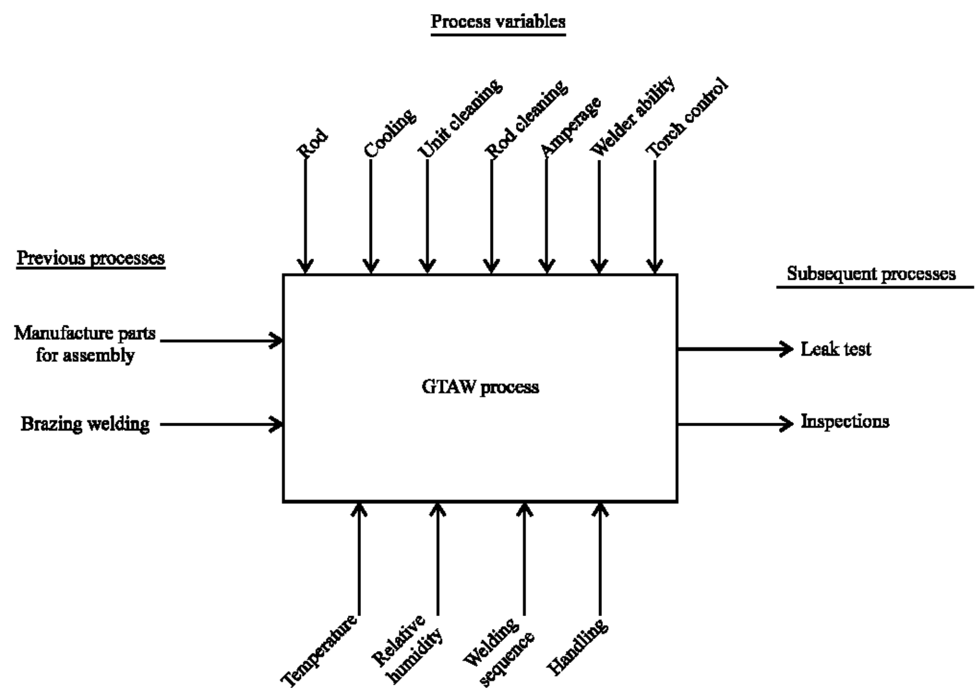

Fig. 1: Box diagram for previous and subsequent processes of GTAW

During analysis of welding process it is important to identify the relationships that each welding parameter has with the general process. Figure 1 identifies each potential variables of the welding process in relation with processes.

Response variables: In most production processes exists quality failures or errors that are usually analyzed and put under a strict control plan which will ensure weld quality. In the welding process, there are also different types of rejections or welding defects, like: Pores, cracks, lack of penetration, external leakage, contamination, incomplete weld and undercut. Figure 2 shows the characterization of defects more common in heat exchangers.

Rework operations of welding process are performed in workstation, once the operator detects some quality errors. Figure 3 displays a defect accumulation diagram that identifies the locations where most of defects on the heat exchangers are found.

Statistical analysis

Taguchi's welding experiment: As a first phase and given the number of potential variables, a Taguchi L_8 orthogonal array will be performed. Table 2 present Taguchi's L_8 orthogonal arrangement used to carry out the experiment. Once completed the eight tests of experimental design by the methodology of Taguchi, it was realized the statistical analysis of the data starting with the ANOVA (analysis of variances). Subsequently, Fisher found new methods of analysis for researchers and gave them a tool to analyze data with more than two conditions or independent variables (Christmann, 2011). It was necessary to

Table 2: Taguchi's L_8 orthogonal array

	Variables						
Test	V	E	U	A	H	L	S
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

No. 1 means the factor will evaluate in it lower specification limit and number 2 in its upper specification limit

Table 3: Taguchi's L_8 orthogonal array and response variables on experimental tests

								Response veriables		
	Variables							Types of inspection		
Test	V	T	U	A	E	L	S	1	2	3
1	1	1	1	1	1	1	1	16	0	1
2	1	1	1	2	2	2	2	2	0	2
3	1	2	2	1	1	2	2	4	0	1
4	1	2	2	2	2	1	1	6	2	8
5	2	1	2	1	2	1	2	5	5	3
6	2	1	2	2	1	2	1	3	0	1
7	2	2	1	1	2	2	1	7	0	1
8	2	2	1	2	1	1	2	2	4	2

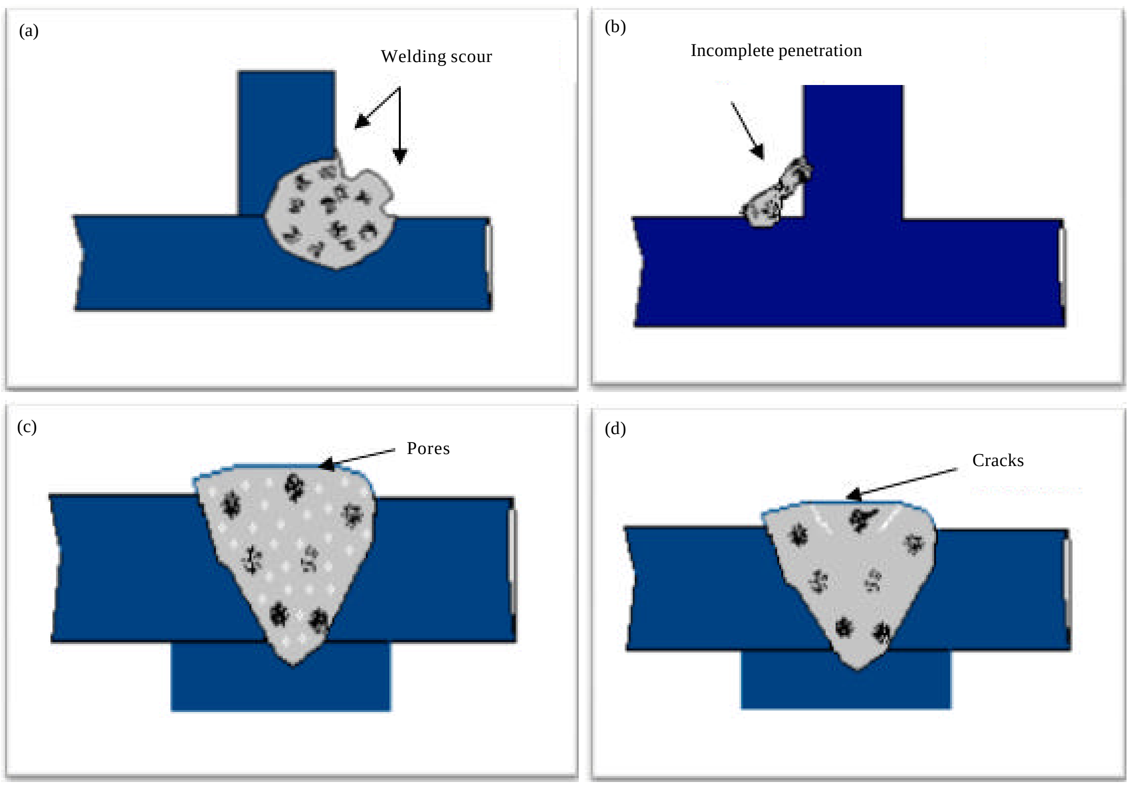

Fig. 2(a-d): Characterization of welding defects, (a) Scour in a melted groove into the base metal at the bottom side of the weld or in the weld root can be touched with the thumbnail, the scour at butt joints is very easy to detect, (b) Happens by conditions in the root of the union in which the weld metal does not exceed the thickness of the joint. Without penetrating areas and without merging is a discontinuity described as incomplete penetration at the junction, (c) Pores is a type of discontinuous hole formed within weld by gas trapped during solidification. One common cause of porosity is contamination during welding and (d) Shrinkage in all welding and bonding or any portion of it, as in the heat affected zone can not be accommodated due to shrinkage stress produced by plastic deformation, then stress will develop very strong. This stress can cause cracks

calculate the ANOVA for each type of inspection method due to their difference. The three types of inspection and results of experimental tests are given on Table 3.

With ANOVA analysis were obtained results of averages for significant variables in terms of defects for each type of inspection. Results are given on Table 4.

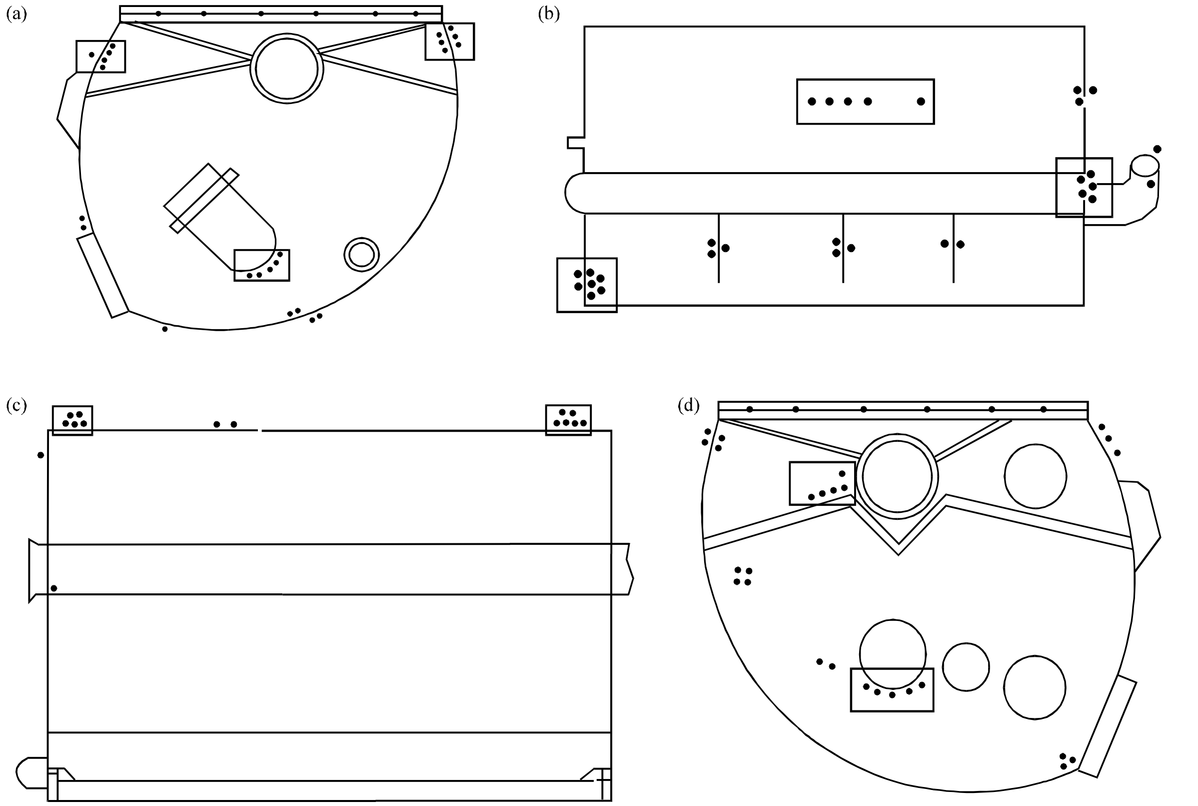

Fig. 3(a-d): Defect acumulation diagram for sketch views of heat exchanger, (a) Left view heat exchanger sketch, (b) Front view heat exchanger sketch, (c) Back view heat exchanger sketch and (d) Right view heat exchanger sketch, dark marks display the defect areas on heat exchangers

Table 4: Average of significant variables from type of inspection

	Types of inspection		
Variables	1	2	3
V_1	7.00	0.50	*
V_2	4.25	2.25	*
T_1	*	*	*
T_2	*	*	*
U_1	*	*	1.50
U_2	*	*	3.25
A_1	8.00	*	1.50
A_2	3.25	*	3.25
E_1	*	*	1.25
E_2	*	*	3.50
L_1	7.25	2.75	*
L_2	4.00	0.00	*
S_1	8.00	0.50	3.50
S_2	3.25	2.25	1.30

A comparison of results among the three methods of inspection was analyzed by determining the levels of significance of each factor in terms of quality defects. The results are shown in Table 5.

The best conditions of each type of inspection using ANOVA statistical analysis are: Rod type on level 1, unit cleaning on pre-brazing area level 1, amperage level 2, electrode type level 1, rod cleaning level 2. For variable of welding sequence (S) will be necessary to review the implication of this variable as it seeks to optimize for a particular conclusion, given the results contradict in Table 6.

RESULTS AND DISCUSSION

After carrying out the experimental tests the results of variables that were statistically significant were: Rod type, unit cleaning on pre-brazing area, amperage, electrode type and rod cleaning. The optimal levels on each significant variable were: Rod type on level 1, unit cleaning on pre-brazing area level 1, amperage level 2, electrode type level 1 and rod cleaning level 2. With recommended conditions variables GTAW defects were reduced by 36%, increasing level of productivity and reduced production costs. Figure 4 displays a radar graph with the recommended levels for significant variables.

Taguchi's experimental methodology is recommended for this type of process because production

Table 5: Comparative levels analysis of statistical significance variables given type of inspection

		Types of inspection					
		1		2		3	
Variables	Description	LSL	USL	LSL	USL	LSL	USL
V	Rod type	○		●	◒		
T	Cooling time						
U	Cleaning unit in pre-brazing area					●	◒
A	Amperage	○	●			◒	◒
E	Electrode type					●	◒
L	Rod cleaning	○	●		●		●
S	Welding sequence	○	●	●	◒		

(●) The effect is clearly significant, (◒) The effect seems to be signficant, (○) The effect might be significant but is probably not

Table 6: Comparative table of significant variables for response variables

	Response variable					
	Types of inspection					
	1		2		3	
Variable	L_1	L_2	L_1	L_2	L_1	L_2
V			●			
T						
U					●	
A		●				
E					●	
L		●		●		●
S		●	●			

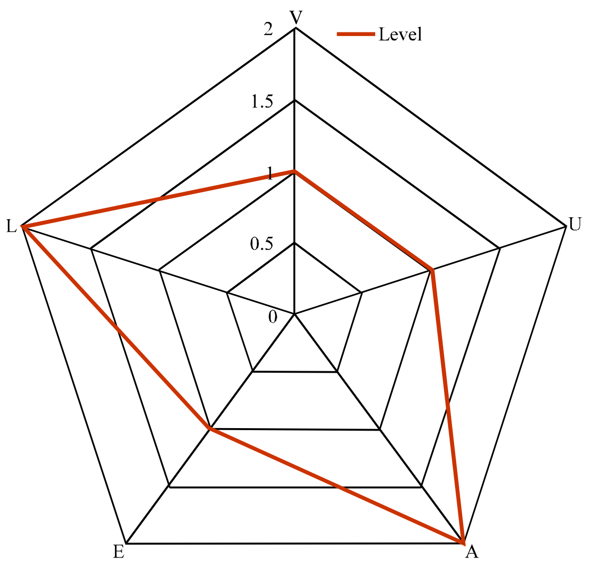

Fig. 4: Radar graph recommended levels for significant variables

rate for steel heat exchangers is low, in addition to a large number of factors. One of the main goals of this methodology is to minimize losses caused by variation, this investigation optimize the welding process in steel heat exchangers with recommended levels to reduce quality defects in GTAW.

Results obtained for significant levels of each factor were performed through ANOVA analysis which is a measure for experimental data. The objetive of this technique is to separate the process variation and experimental error.

After this first phase, some actions were planned:

- Continue the investigation testing the optimal scenario for each significant variable
- Carry out a cost analysis to evaluate the improved welding process

There are several researches where statistical techniques for solving problems in welding processes are used; one of the contributions mentioned in introduction section is the importance of the planning phase. In this project it is discovered how significant it is and time it takes to do the proper planning experimentation e.g., the personnel involved, process characteristics, controlled factors and noise factors which were identified and developed during the investigation. Other important contributions in the field of design of experiments using the Taguchi methodology were considering the response variables in terms of stress tests such as stress and elongation. For this project the response variable in welding process was considered in terms of defects, were the recommended optimum levels found of the significant factors reducing quality defects.

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