

Characterization of Welding Process Using Optimal Design of Experiments and Fedorov Analysis

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Abstract: In the automotive sector, there are different techniques used for joining two metal components of a harness. In some cases, joining through welding is required. Often, this industry focuses on fault detection and not on preventing them. A robust parameterization and prevention approach could help to avoid imperfections in the joining of the pieces: the quality of the weld can be evaluated by conducting destructive and non-destructive testing. The objective of the present work is to define the optimum process parameters in order to increase penetration. To achieve this objective, the variables of time, current, squeezed time, penetration and force will be studied to quantify the correlation level. This will be done utilizing a design of experiments with a confidence level of 95% using the Fedorov statistical technique.
Key words: Optimization, Welding Process, Parameterization, Resistance Welding

Introduction

Within vehicle control and connection systems, there are the electric harnesses which are an assembly of a set of circuits. The primary function is to transmit electrical signals to all vehicle systems. In Fig. 1, we can observe a representation of a set of harnesses in a car. According to Trommnau et al. (2019), the wire harness is used in automobiles to connect electronic components, control units, sensor and actuators, which is a component, device or machine that helps to achieve a mechanical movement by converting energy.

The union of two components of a harness can be carried out using different techniques: one of them is the joint through welding. The assembly of a harness set must possess certain conditions and characteristics to provide a continuous and reliable electrical signal. Some of these conditions refer to the type of material, the caliper of the wire, protectives, and reliable joints, the latter being one of the most critical components.

The primary disadvantage of the welding process is that defects are challenging to detect, and specialized equipment is required to visualize them. Consequently, the strength of the joint can be affected. Besides, the probability of part fatigue is increased due to the mechanical properties of the welded components (Stavridis et al., 2018).

Defects or imperfections in the welding of an automotive harness represent a risk for the vehicle user. The failure of a car to perform its function puts the life of a person at risk in the worst-case scenario. The automotive industry demands high levels of quality standards throughout the production chain. The material properties, welding tools, and critical process parameters must be taken into account in the formation of faults and the welding quality.

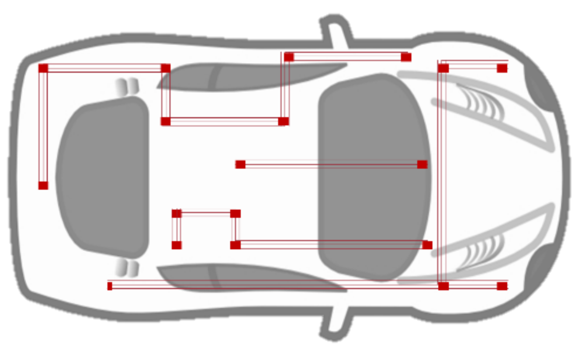

Figure 1. Representation of a set of harnesses in a car (Source: own elaboration).

In order to meet these parameters, it is important to understand the process of welding. Welding is the process of joining materials through heat and pressure, where the contact surfaces of two or more pieces are melted. It is a versatile assembly technique mostly because it is considered easy, fast and can be applicable to most of the major commercial metals. As different authors (Ahmed & Kim, 2017; Amiri et al., 2020; Boriwal et al., 2017; K. Y. Kim

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& Ahmed, 2018; Zhou & Yao, 2019) have demonstrated, the process of welding involves mainly three important variables: the current, the force, and the welding time.

The most common uses of welding are in construction, pipe production, in the aerospace industry, railway industry, and the automotive industry. These different sectors utilize many different techniques and types of welding in various processes that require the joining of metals, welding types that can be divided into two major classifications: fusion and solid-state, as represented in Fig. 2. The different types of welding are consequently reviewed.

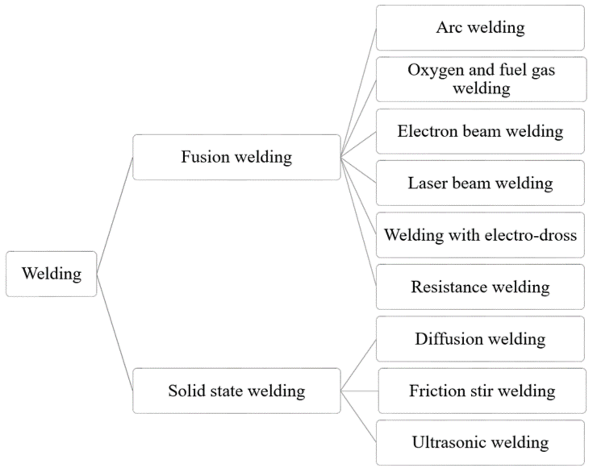

Figure 2. Welding classification (Source: Own elaboration).

Solid-State Welding

Solid-state welding produces joints at temperatures below the melting point of the primary materials. These are usually free of solidification defects and do not require the use of shielding gas, filler metal, or fluxes (Nee, 2015). In diffusion welding, a part is held under pressure for a long time at a high temperature. This welding is determined by the temperature and the time of permanence (Gietzelt et al., 2017). Friction welding is done with a rotary tool with a specific profile that moves forward along the welding line. The friction between the tool and the workpiece is responsible for the generation of heat and the softening of the material. As the tool advances, the weld is formed by the agitation of the material (Dialami et al., 2017). Ultrasonic welding is based on vibration. The part of being assembled vibrates against a stationary part. This vibration causes the generation of heat that melts the materials to form the joint. The quality of these joints depends mostly on the welding parameters (Kalyan Kumar & Omkumar, 2020).

Fusion Welding

Fusion welding uses heat to melt the base metals. Sometimes a filler metal is added to add volume and give strength to the joint. Fusion welding can be subclassified into: arc, oxygen, and fuel gas welding, electron beam, laser beam, electro slag, and resistance welding. Arc welding performs the fusion of metals through the heat generated by a current discharge (Juan & Maturana, n.d.). Oxygen and fuel gas welding is performed using a hot flame, where the flame comes from the combustion of oxygen that acts as an oxidizer. It is directed by employing a torch. To this welding, a filler metal can be added (Principal et al., 2006). In electron beam welding, no fluxes or filler metals are required; it is generated by a concentrated current of high-intensity electrons, causing the necessary heat to melt the metals (Chiumenti et al., 2013). Laser welding is done through the energy produced by a highly concentrated light beam. Welding with electro-slag is done by melting some slag that conducts heat to the base and filler metal (Claro et al., 2015). Resistance welding is used in the assembly process of automotive electrical harnesses. It requires an electrical resistance that carries the current flow with which the metal surfaces held under pressure are heated (Dobránszky et al., 2012).

Resistance spot welding (RSW) is the specific type of welding that we will study in this investigation; a deeper dive into the process is shown next.

Resistance Spot Welding

Authors have demonstrated that RSW is based on Joule heating by passing a short and high current between electrodes through the overlap of the material to be joined (T. Kim et al., 2005). The equation (1) represents it, where Q denotes de energy delivered into the welding system in Joule, t_1 and t_2 respectively denote the beginning and terminating time of the welding action, I(t) is the welding current, R(t) is the total resistance between two electrodes, in general cases, the resistance of the welding load dominates the total resistance (Zhou & Yao, 2019). The process consists of a squeezed time, during which a force is applied to the joint by the electrodes before applying the current flow (Phase 1). Then a contact resistance is created (Phase 2). Subsequently, the welding current is applied to the part for a specified time. The flow of current through the resistance contact between the metal produces heat and causes the metal to melt, generating the joining of the metals (Phase 3). This joint is known as a nugget. The next step is when the welding current is then arrested, and pressure continued to coalesce the weld for some time (hold time) while the weld solidifies (Phase 4). Then the electrodes stop intercepting the parts (Phase 5). Figure 3 illustrates the sequence of the five main phases of the RSW process.

$$Q = \int_{t_1}^{t_2} I^2(t)R(t)dt \quad (1)$$

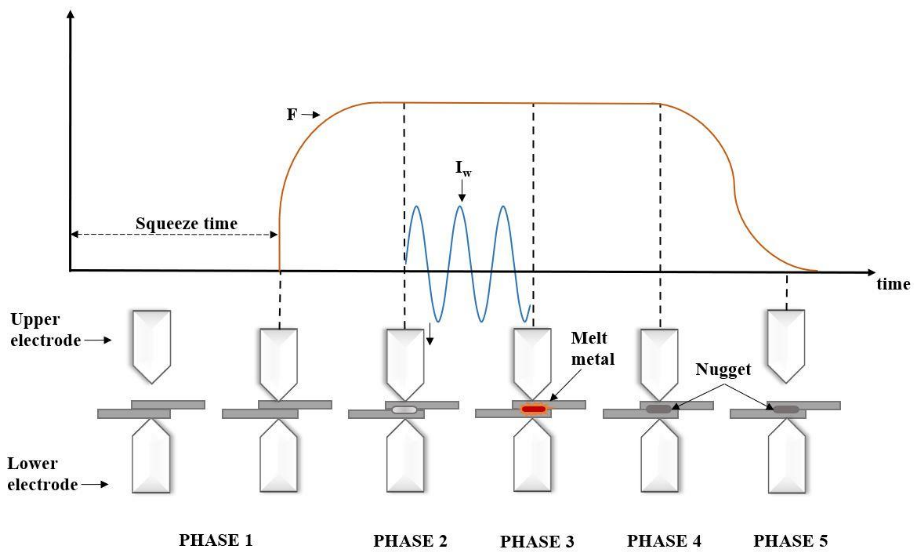

Figure 3. Five main phases of the Resistance Spot Welding process (de Almeida et al., 2018).

Welding Parameters

In the welding process, there are three parameters that determine the process and the quality: current, time, and electrode force. In the research of Zhou and Yao (2019), it is mentioned that a minimum value of current can induce a cold weld, while an excessive current will generate an expulsion. On the other hand, a too-small value of electrode force may quickly induce expulsion, while a considerable value of electrode force may reduce heat energy efficiency and produce small weld because of no sufficient contact resistance and consequently heat generation. Consequently, there are researchers who look for good weld quality by optimizing the parameters. Several techniques can be used to select the optimum welding parameters. One of them is the Design of Experiments (DoE). According to Vanaret et al., (2021), the DoE aims to suggest some experiments as informative as possible, such that the parameters of a model may be estimated as reliably as possible. Ideally, forming the DoE optimization problem requires the knowledge of the model parameters, oftentimes whose valid values are unknown. In the article published by Pronzato (2008), some of the purposes of DoE are mentioned, such as problem-solving through optimization, estimation, prediction, and control.

For the present investigation, we define the tensile strength as dependent on the parameters of penetration, time, current, and force. For each of the four factors, the expected values (μ) of Y are compared for each level of the experiment, in this case two for each factor.

$$H_0: \mu - 1 = \mu + 1 \text{ ; } H_1: \mu - 1 \neq \mu + 1 \quad (2)$$

Equation (2) represents the null and alternative hypothesis. The null hypothesis states that the expected values are equal, in other words, there is no significant difference in the expected values of pull force test. The alternative hypothesis states that the expected values are different.

The objective of the present work is to define the optimum process parameters in order to increase penetration. To achieve this objective, the variables of penetration, time, current and force will be studied to quantify the correlation level and determine which are the most significant parameters.

Methodology

The experiments were carried out in a company that produces harnesses. The company is an Austrian-owned corporation established in Mexico. It is considered a large size company with 450 employees. In order to respect the privacy of the company, the name is not revealed. The postgraduate program with industry of the National Council of Science and Technology (CONACYT) of Mexico allows employees to study and develop projects that promote scientific research and industrial application within the companies themselves; through this program, the present researchers were able to identify and reach out to the company and utilize them as the site and subjects of this investigation.

In this research, the components were welded according to the table that was generated using an optimal design of experiments using the Fedorov statistical tool in R software. The purpose of optimization is to find an optimum combination of the parameters for a special welding process, and the goal is obtaining welds with higher tensile-shear strength.

Materials and Methods

The welded material used in the experimentation was composed of two wires with copper-tin alloy (Cu/Sn). The first wire, labeled wire A, contained 28 strands with a cross-section of 0.50mm^2. The second, wire B, had 19 strands and a cross-section of 0.35 mm^2.

For the welding equipment, a semi-automatic machine was used, which utilizes two flat tungsten electrodes (Wl). The upper one has a diameter of 0.8*5*15.5 mm with opposing polarity, and the lower one has a diameter of 0.8*5*18.5mm with positive polarity.

Results and Analysis

The selected parameters and their magnitudes were selected according to the limits and settings allowed by the welding machine. The parameters are (A) penetration, (B) time, (C) current and (D) force. The minimum and maximum values are shown in Table (1).

TABLE I
PARAMETERS AND LEVELS

Parameter	Level	
	1	2
Penetration	150	300
Time	80	200
Current	1000	2000
Force	300	400

Design of Experiments and Fedorov Analysis

An optimal design of experiments was developed to determine the variables that influence the welding process. The Fedorov analysis was used to optimize the experiment and obtain the least number of experimental runs. The efficiency of the experiment was greater than 80%. The array is presented in Table 2.

TABLE 2
FEDOROV ARRAY

	Input Parameters					Output Parameter
Exp. No.	Force (N)	Squeeze Time (ms)	Current (A)	Time (ms)	Penetration (μm)	Tensile Strength (N)
1	400	200	1000	80	150	3.1
2	400	700	2000	200	150	72.5
3	300	200	2000	80	300	77.3
4	300	700	1000	200	300	65.15
5	400	700	1000	80	150	6
6	300	700	2000	80	150	87
7	300	200	2000	200	150	62
8	400	200	2000	80	300	87.05
9	400	200	1000	200	300	40.85
10	300	200	1000	80	150	7.75
11	400	200	2000	200	150	78.3
12	400	700	2000	80	300	86.85
13	300	700	1000	200	300	43.3

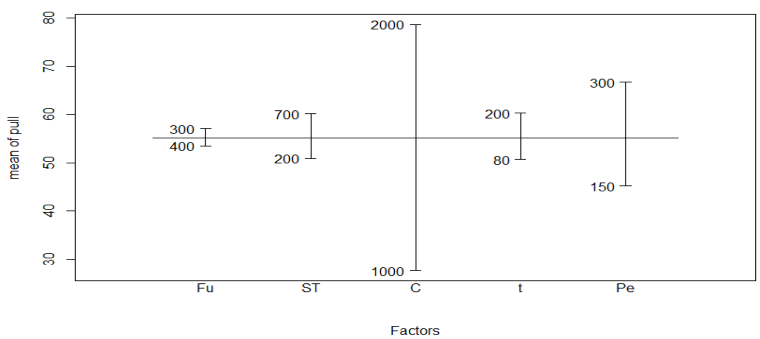

Figure 4. Main effects plot of tensile strength.

In Figure 4, significant effects are shown, based on the results of the experiment performed through an ANOVA. Based on the Sum, Mean, and F Value, the results show that the current is the factor that most strongly affects the quality of the weld.

TABLE 3
ANOVA TABLE

Response: Tensile Strength

	Df	Sum sq	Mean Sq	F Value	Pr (>F)
Current (A)	1	8410.7	8410.7	47.737	$4.148e^{-05}$
Penetration (μm)	1	2055.4	2055.4	11.666	0.006596
Residuals	10	1761.9	176.2		

The tensile strength testing was performed in this experiment to determine which factor or factors are significant in the welding process. According to the last reduced ANOVA model obtained, the current is the most significant factor. The value of the R-squared corresponds to 85.6% and adjusted R-squared correspond to 82.7%, indicating that the model is a predictive model (illustrated in Table 4)

TABLE 4
ANOVA SUMMARY TABLE

Coefficients:

	Estimate Std.	**Error**	**t-value**	**Pr (>| t |)**
(Intercept)	15.0048	6.563	2.293	0.0448
Current 2000A	52.829	7.404	7.136	$3.16e^{-05}$
Penetration 300 µm	25.288	7.404	3.416	0.0066

Residual standard error: 13.27 on 10 degrees of freedom
Multiple R-squared: 0.8559, Adjusted R-squared: 0.8271
F-statistic: 29.7 on 2 and 10 DF, p-value: $6.21e^{-05}$

In Figure 5, the effects of current and penetration on the tensile strength test can be seen graphically. The current and the penetration are sufficient factors to guarantee higher tensile strength values than the minimum specification value required by the customer.

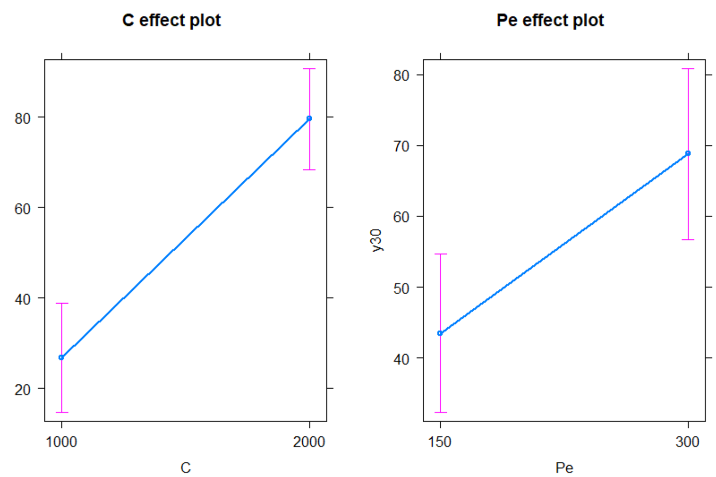

Figure 5. Effects plot of Current and Penetration on tensile strength.

In table 5, the highest tensile strength values demonstrate that by setting the current at 2000 A, we will obtain tensile strength test results at approximately 79 N.

TABLE 5
EFFECTS OF CURRENT AND PENETRATION ON TENSILE STRENGTH

Current	**1000 A**	**2000 A**
	26.72 N	79.55 N
Penetration	**150** µm	**300** µm
	43.49 N	68.78 N

Conclusions

The experiment presented in this research was conducted using an optimal design of experiments. R software was used to determine the experimental array using the Fedorov algorithm. We can conclude that the current is the most significant factor using a 95% confidence level. Also, the current and the penetration are sufficient factors to guarantee higher tensile strength values than the minimum specification value required by the customer. The R-squared and adjusted R-squared values are greater than 80%, which indicates that our model is a predictive model. Last, we emphasize that by working the current at 2000 A, it is possible to obtain tensile strength test results at approximately 79 N.

With these results, we can conclude that the parameters are fundamental to determine the quality of the weld, and specifically that the current parameter can help to guarantee that the weld is correctly joined. These studies can help companies to parameterize their equipment to obtain high quality products based on statistics.

Furthermore, a clear benefit of utilizing optimized experimental designs such as the one in this present investigation is that it reduces the cost of investment in materials and the time that would otherwise be spent in production to repeatedly perform the experiments. This is due to the fact that by the use of these experiments we obtain the least amount of runs obtaining the most significant results.

Limitations

One of the constraints for performing this investigation was to obtain the availability of the machine. It was difficult to gain access to the machine given that it is utilized on a busy schedule by a presently working organization; However, being able to experiment on this machine would allow for more accurate results, as it is used for the production of automotive harnesses.

Recommendations

For future investigations, we emphasize the importance of obtaining representative results in the research and experimental designs. It is necessary that the process is within control, otherwise, the results obtained may generate a bias. In other words, first we recommend that for follow up investigations, the statistical characterization of the process be performed to determine the normality of the process, estimate the mean, and the standard deviation. From these baseline results, it is possible to calculate the process capability. If our process is not in control, there will be special causes such as a damaged component, an inappropriate measurement system, incorrect operation of the machine, etc. This generates results that will not be useful to parameterize the equipment.

From the results obtained, a logical next step of research is to continue the analysis that can determine the optimal values of the significant factors. This can be done through a response surface model.

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