



Optimization of Ultimate Tensile Strength with DOE approach for application FSW process in the aluminum alloys AA6061-T651 and AA7075 -T651

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ABSTRACT. Friction stir welding process is increasingly used to connect metal structures for industrial applications as shipbuilding and offshore, aerospace, automotive, rolling stock for railways and robotics, Friction stir welding makes it much easier for us to fusion the aluminum alloys like AA6061-T651 and AA7075 -T651. it is essential to carefully study to contain many parameters such as the welding speed, the rotation speed and the type of pin used during the operation to optimize mechanical properties and in particular to obtain high rupture strength with the tensile test.



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In this paper we aim to treat carefully this process by using the design of experiment method which is an original approach that resides in the possibility of interpretation of experimental results with a minimal effort on the experimental level whichever generates the minimization of the necessary number of experiments and allows a saving in time and in financial cost. For each parameter, the effect of interaction with the rotation speed, the welding speed and the choice of the pin, were determined. A mathematical model between the response and the parameters are modeled, which represents the analytical part of this optimization.

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KEYWORDS. FSW welding; Rupture strength; Design of experiment; optimization UTS.

INTRODUCTION

The welding process goes back to the discovery of metals, and since the latter has not stopped evolving as technologically, but also on the methods and working conditions. In 1991 the British Institute (the Welding Institute) invented a new ecological and efficient process especially for aluminum alloys as well as other alloys complicated to weld by conventional methods, this process known as Friction Stir Welding FSW[1-3].

This technique, which is currently used in many sectors, consists of assembling two metal sheets by friction and local mixing, using a tool. The latter is placed between the two sheets to create the weld joint, by significant rotational action and a force exerted underneath, causing plastic deformation, we can create an effective weld without ever reaching the melting temperature of the base metal[4-7].

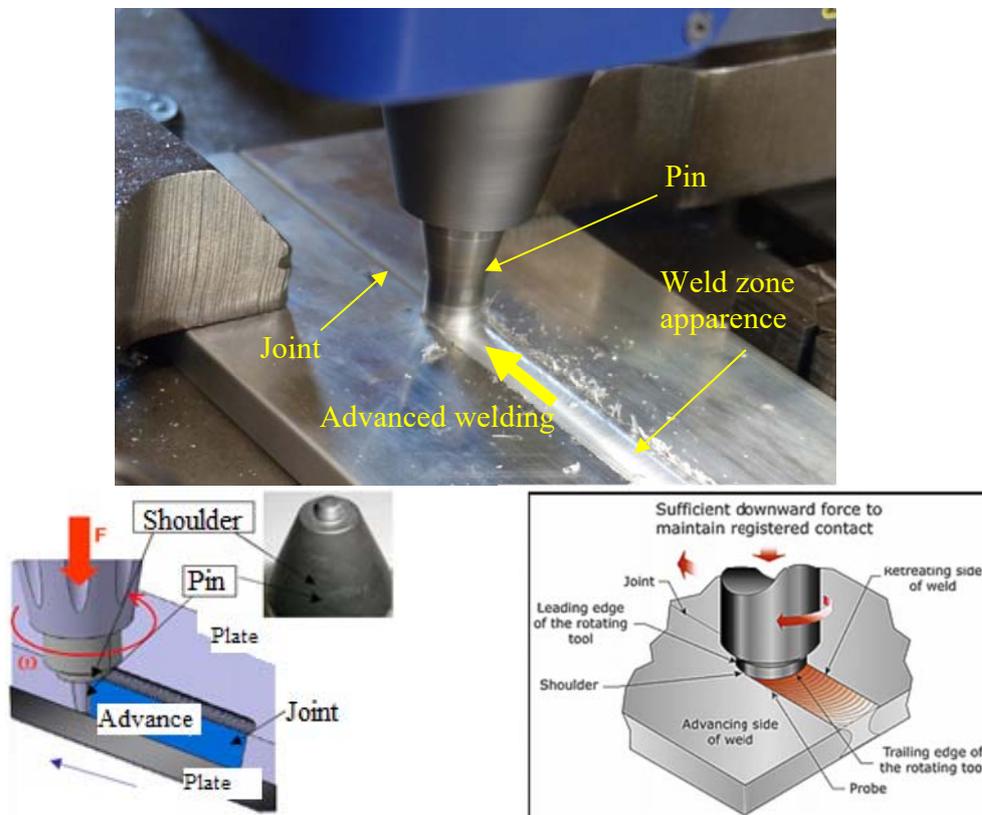


Figure 1: Schematic representation of FSW principle [8].



This process allowed us to use more and more the alloys of non-ferrous metals which offer important mechanical characteristics[9, 10], it also contributed to reduce the manufacturing costs[11, 12], that is why we find so important, to focus our research on how to optimize the operation at low cost, while controlling the parameters, with the best plausible configuration, which will play a crucial role in the maintenance of structures, like the speed of the tool and welding, but also the tool geometry (Fig. 2).



Figure 2: Friction stir welding tools with different pin profiles [13].

In industrial processes, it is useful to explore the relationships between the key variables (or factors) of the input process and the output performance characteristics (or quality characteristics) [14]. For example, in a metal shotpeening operation, the impact velocity, the processing time that induces the coverage rate, the shot's hardness, can be treated as input variables and the quality of the surface will be considered as performance characteristic so an answer[15].

Design of experiment (DOE) is a robust technique used to explore new processes, gain insights into existing processes, and optimize these processes to achieve world-class performance [16, 17]. Many researchers have been involved in the use of DOE since the mid-1990s to promote mathematical and statistical skills[17, 18], Yunus et al [19] also reported how Genetic programming can be applied to the FSW process to derive precise relationships between the output and input parameters in order to obtain a generalized prediction model.

Though the welding is a controlled process, we aim in this article to get more knowledge and skills by using the DOE, that helps to supervise much more the operation at a lower cost.

OPTIMIZATION BY THE DESIGN OF EXPERIMENT METHOD

In this paper, an experimental design method was used on the FSW friction stir welding process, basically using parameters that effect the process, such as rotational speed, welding speed, and profile. pin which carries a surface ratio (S_s / S_d) representing the type of the pin, where S_s / S_d represents the ratio between the area occupied by the pin in static state and the area occupied by the pin in dynamic state.

For example, in the case of a round pin, the surface ratio is equal to 1 and in the case where the pin is square, the ratio 1.57 is found.

We focused on the welding area, which consists of two different materials, the AA6061-T651 and the AA7075-T651 elaborated by the friction stir welding method, with decrypting the parameters which are the speed of rotation and welding through the pin profiles on tensile strength of joints. Two types of H13 steel tools have been used to fabricate welded joints with different pin profiles.

we have Based on the results of Ravikumar [18], which studied the influence of welding parameter variation on the rupture strength. However, we have well expolited this data by the DOE method to highlight such a deep and profound analysis.

Tab. 1 shows the FSW welding parameters and their working ranges of AA6061-T651 and AA7075 -T651.

N°	Parameters	Symbol	Unit	Level	
				Low (-1)	High (+1)
1	Rotational speed (rpm)	R	rpm	800	1000
2	Welding speed (mm/min)	S	mm/min	90	100
3	Pin profile	P	-	Cylindrical (1)	Square (1,57)

Table 1: Process parameters with different levels



MATRIX DESIGNS

The purpose of the experimental design can be defined as a means of reducing the number of trials with maximum precision.

We can use a unique coding relation defined from the bijective transformation defining the value x_i from relation (1), which deals also the plans to study the response surface [20]:

$$X_i = \frac{u_i - \left(\frac{u_{i\max} + u_{i\min}}{2} \right)}{\left(\frac{u_{i\max} - u_{i\min}}{2} \right)} \quad (1)$$

$u_{i\max}$ and $u_{i\min}$ being the limits defined by the experimenter and u_i the real level given to factor i . The coded factor X , has values in the bounded interval between [-1; 1].

We obtain a complete factorial plan with k factors at two levels by the combination of each two levels of this factor[21]. Our matrix of experiences of three factors is represented by Tab. 2. The Fig. 7 represents the experimental points located at the vertices of a hyper cube which forms a named space, the experimental field of study.

The effects and the interaction of the factors given in a matrix of experiences of type 2^k on a well determined response, can be estimated by the values of the coefficients of a mathematical model of the polynomial type of the first degree, which translates the relation between the answer y and the factors X_i .

The response y , of a mathematical model in the case of a plane 2^3 is defined by the relation:

$$y = a_0 + a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_3 + a_{12} \cdot I_{12} + a_{13} \cdot I_{13} + a_{23} \cdot I_{23} \quad (2)$$

a_0 : The general average.

a_1, a_2, a_3 : Effect of the rotational speed, the welding speed and the profile of the pin respectively.

a_{12} : Effect of the interaction of the rotation speed and the welding speed.

a_{13} : Effect of the interaction of the rotation speed and the pin profile.

a_{23} : Effect of the interaction of the welding speed and the pin profile.

I_{12}, I_{13}, I_{23} : Interaction between the different variables.

N° Test	Rotation speed (rpm) (R) \equiv (X1)	Welding speed (mm/min) (S) \equiv (X2)	Pin profile (Ss/Sd) (P) \equiv (X3)	Rupture strength -UTS (MPa) (Y)
01	800	90	1	174
02	1000	90	1	184
03	800	100	1	186
04	1000	100	1	188
05	800	90	1.57	150
06	1000	90	1.57	172
07	800	100	1.57	160
08	1000	100	1.57	175

Table 2: Experimental matrix.

A system of 8 equations with 8 unknowns is generated by the mathematical model resulting in a set of results from a plane of 2^3 , if we neglect the experimental errors. We can form this system in a matrix form according to the relation (3):



$$Y = X.a \tag{3}$$

with:

Y: vector of responses represented by a column matrix $(2^k, 1)$,

a: vector of the effects of the factors and all the interactions, represented by a column matrix $(2^k, 1)$; these components are the unknowns that we are trying to determine,

X: square matrix $(2^k, 2^k)$ composed of - 1 and + 1 according to the values of the levels xi.

The relation (10) represents the matrix form of our plane 2^3 system:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 & -1 & 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \\ 1 & -1 & 1 & 1 & -1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_{12} \\ a_{13} \\ a_{23} \\ a_{123} \end{bmatrix}$$

The orthogonality of our matrix is a very important property because the inverse of X is equal to the transpose of X divided by the number of lines n [22]. Indeed, according to Hadamard, we have the relation (4):

$$X'X = n.I \tag{4}$$

with I represents the unit matrix and

X': is the transposed matrix of X.

I: the identity matrix.

n: the number of experiments performed (n must be a multiple of 4).

From relation (4) and taking account of relation (5), we can calculate the unknown a:

$$\left. \begin{aligned} X' y &= X' X . a \\ X' y &= n . I . a \\ a &= \frac{1}{n} X' y \end{aligned} \right\} \tag{5}$$

The elements of a are calculated in the following form:

$$a_i = \frac{1}{n} [\pm y_1 \pm y_2 \pm y_3 \pm \dots \pm y_n] \tag{6}$$

Tab. 3 is used which defines the calculation matrix to gather all the tests carried out. It is made up of several columns; the first column represents the average of the different tests, the other parameters express the state of the coded factors, each column represents a factor. The responses obtained are indicated by the last column [23].

We obtain the following adjusted mathematical model using the least squares method:

$$y = 173.625 + 6.125 X_1 + 3.625 X_2 - 9.375 X_3 - 1.875 I_{12} + 3.125 I_{13} - 0.375 I_{23} + 0.128 I_{123}$$

$$UTS = 173.625 + 6.125 R + 3.625 S - 9.375 P - 1.875 RS + 3.125 RP - 0.375 PS + 0.128 RSP$$



Fig. 3 shows the geometric state of the experimental design.

N° Test	Average	X ₁	X ₂	X ₃	I12	I13	I23	I123	UTS (MPa) (Y)
01	1	-1	-1	-1	1	1	1	-1	174
02	1	1	-1	-1	-1	-1	1	1	184
03	1	-1	1	-1	-1	1	-1	1	186
04	1	1	1	-1	1	-1	-1	-1	188
05	1	-1	-1	1	1	-1	-1	1	150
06	1	1	-1	1	-1	1	-1	-1	172
07	1	-1	1	1	-1	-1	1	-1	160
08	1	1	1	1	1	1	1	1	175
Effects and interactions	a₀	a₁	a₂	a₃	a₁₂	a₁₃	a₂₃	a₁₂₃	
	173.625	6.125	3.625	-9.375	-1.875	3.125	-0.375	0.128	
Level -		800	90	Cylindrical					
Level +		1000	100	Square					

Table 3: Calculation matrix.

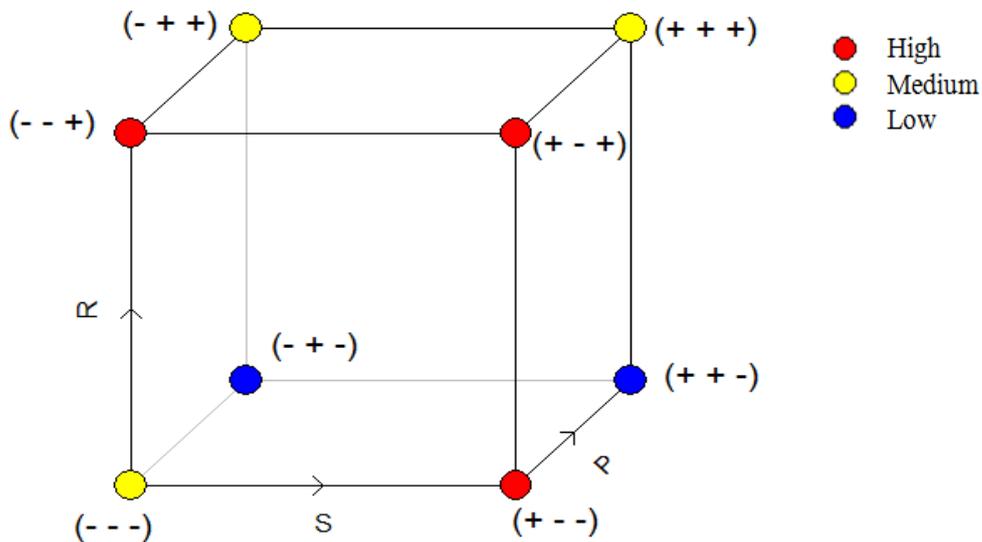


Figure 3: Geometric representation of a plane 2³.

EFFECTS ANALYSIS

Principal effect for each factor

We are basing on complete factorial plan at two levels; we studied in a first case the effect of each factor separately from each other on the rupture strength, with a simultaneous variation and in an ordered manner balanced (Fig. 4).



Fig. 4 shows the evolution of the rupture strength considered as a response (UTS), influenced by the change of the three parameters, rotation speed (X1), welding speed (X2) and the type of pin profile (X3), implied from his low to the high level. We can say that the rupture strength increases during the increase of the factors in the welding operation 800 rpm to 1000 rpm, regarding the rotation speed 90 mm / min to 100 mm / min, in addition the circular pin profile shows a significant advantage compared to the square pin, this manifests including the value of the breaking strength which is included between 183 MPa and 164.25 MPa respectively.

Otherwise, we observe in Fig. 8 that the main effect of the speed of rotation corresponds to approximately 13 units of rupture strength from 167.5 MPa to 179.75 MPa, and 8 units from 170 MPa at 177.25 MPa.

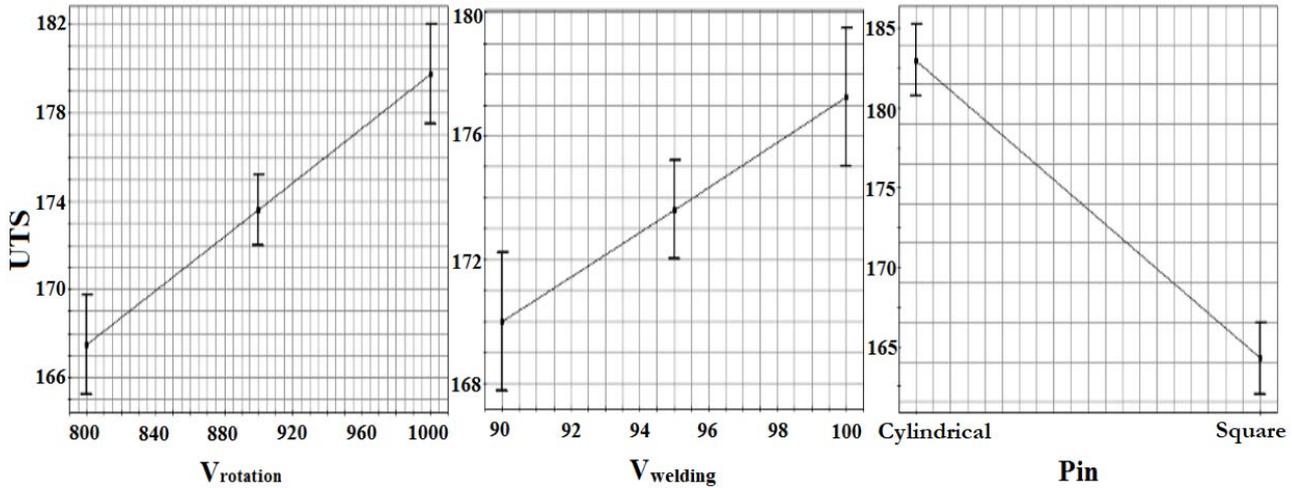


Figure 4: Illustration of the principal effect with three factors.

Interaction effect for two factors

To better understand this effect, we have created specific interaction graphs (Fig. 5).

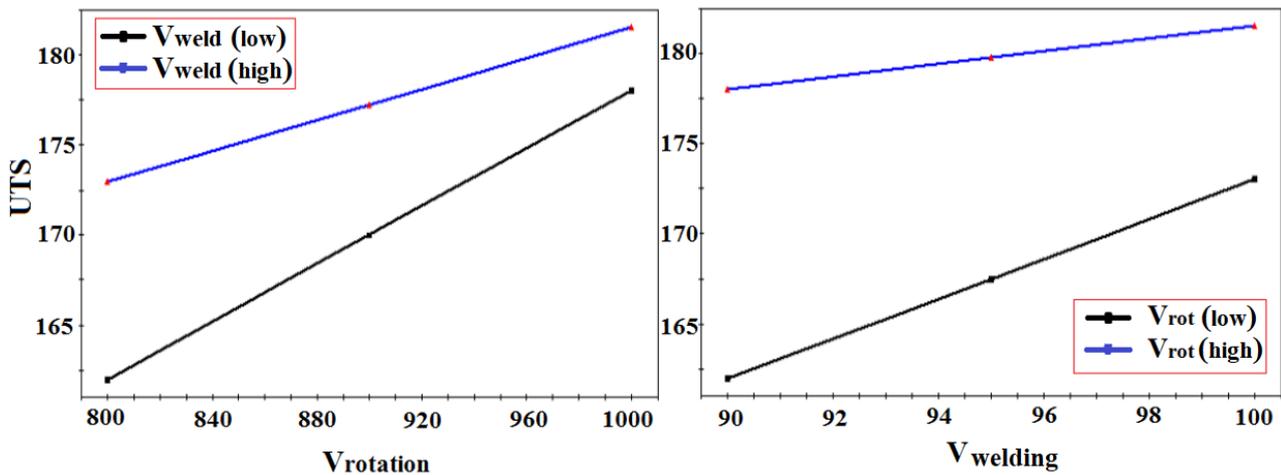


Figure 5: Interaction between rotational speed and welding speed.

Fig. 5-left shows us that the rupture strength increases with the increase of the rotation speed. However, a higher influence of the rotation speed during a higher welding speed compared to the low level. In other words, the effect of the speed of rotation depends on the level of the welding speed and especially if the rotation speed has the smallest value. We also see in Fig. 5-right that the influence of the welding speed is greater when the rotation speed is fixed at its higher level.

In an identical way, it can be seen in Figs. 6 and 7 on the left side, that the rupture strength is improved with highest welding speed and higher rotational speed in the case where the round pin's ratio (S_s / S_d) equal to 1 compared with the ratio of 1.57.



We can clearly see from Figs. 6 and 7 on the right side, that the resistance is low for a square pin with high rotation and welding speed values, it remains greater with a round pin. We also observe that the resistance is modest for a large area ratio.

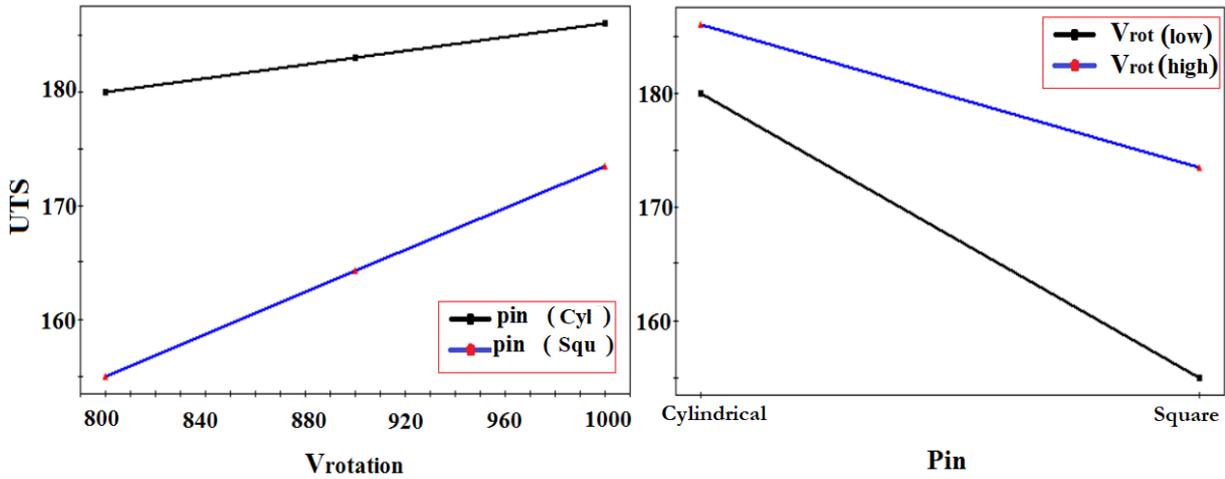


Figure 6: Interaction between the speed of rotation and the profile of the pin.

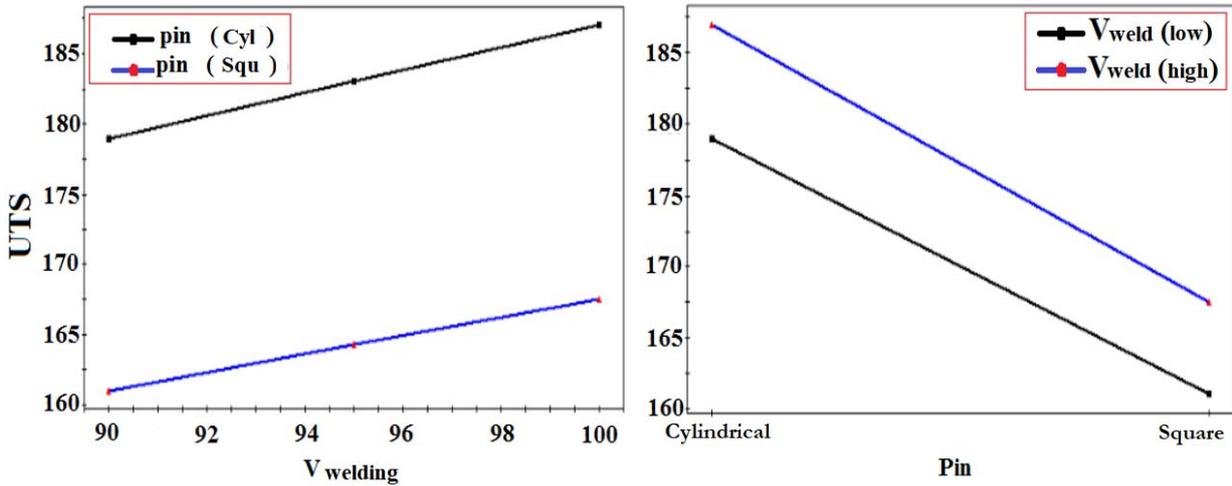


Figure 7: Interaction between the welding speed and the pin profile.

MODEL VALIDATION

Calculation of residuals

According to the calculations made, we can calculate the estimated expenses based on the mathematical model found, we collect all the results in the table indicated below:

To calculate the difference between the experimental response and the predicted (estimated) response, it suffices to use the relation (14) which represents the residue of each experiment.

$$e_i = \left| Y_{\text{exp}} - Y_{\text{estimated}} \right| \tag{14}$$

When adjusting a regression model, the most important diagnostic tool consists of two companion parameters R2 and Q2. The R2 parameter is called the quality of the fit, it is a way of measuring where the regression model can be brought to fit the raw data. When R2 is equal to 1, all the points are located on the diagonal of Fig. 9. Consequently, R2 alone, is not a sufficient indicator to probe the validity of a model.



Also a determination of the parameter of the prediction quality was very important to validate the outcomes of DOE method. Fig. 8 show value of 0.996 which is a more realistic performance indicator, as it reflects the objective of modeling forecasts for new experiences.

y_i	Applied model of each experiment	$y_{\text{predicted}}$
y_1	$190.19 - 4.69 (-1) - 91.53(-1) + 144.03(-1) + 2 (1) - 3.35(1) - 69.48(1)$	71.56
y_2	$190.19 - 4.69 (1) - 91.53(-1) + 144.03(-1) + 2 (-1) - 3.35(-1) - 69.48(1)$	64.86
y_3	$190.19 - 4.69 (-1) - 91.53(1) + 144.03(-1) + 2 (-1) - 3.35(1) - 69.48(-1)$	23.44
y_4	$190.19 - 4.69 (1) - 91.53(1) + 144.03(-1) + 2 (1) - 3.35(-1) - 69.48(-1)$	24.78
y_5	$190.19 - 4.69 (-1) - 91.53(-1) + 144.03(1) + 2 (1) - 3.35(-1) - 69.48(-1)$	505.29
y_6	$190.19 - 4.69 (1) - 91.53(-1) + 144.03(1) + 2 (-1) - 3.35(1) - 69.48(-1)$	485.21
y_7	$190.19 - 4.69 (-1) - 91.53(1) + 144.03(1) + 2 (-1) - 3.35(-1) - 69.48(1)$	179.24
y_8	$190.19 - 4.69 (1) - 91.53(1) + 144.03(1) + 2 (1) - 3.35(1) - 69.48(1)$	167.17

Table 4: Calculation of estimated responses.

y_{exp}	$Y_{\text{estimated}}$	e_i
70.17	71.56	-1.39
66.25	64.86	1.39
24.83	23.44	1.39
23.39	24.78	-1.39
506.68	505.29	1.39
483.82	485.21	-1.39
177.85	179.24	-1.39
168.56	167.17	1.39

Table 5: Calculation of residues.

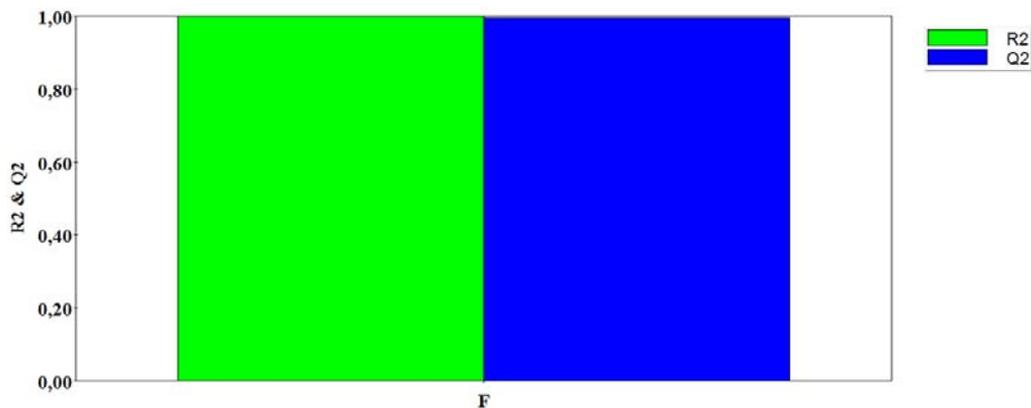


Figure 8: Adjustment parameters.

We can say that the fit is excellent, because all the points are located near the line according to Fig. 09. However, the estimate of the small deviations between the calculated and measured response values is given by the residual standard deviation.

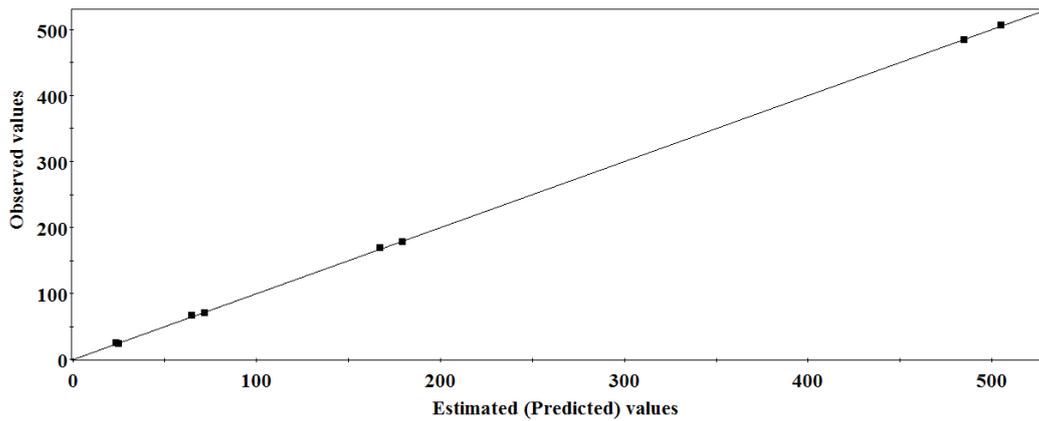


Figure 9: The relationship between the calculated and observed responses of FSW welding.

Signification of effects

We use the Student test given by relation (7) to determine the influence of each variable and each interaction for a chosen risk of 5%.

For a given risk, if an effect is different from 0, it can be considered significant on the studied response.

$$t_i = \frac{|a_i|}{\sigma_i} \quad (7)$$

In order to use the Student table, it is necessary to calculate the degree of freedom as follows:

$$v = n - p(\text{v: ddl})$$

with:

n : is the number of experiments carried out,

p : is the number of effects including the constant (the average).

To find the signification of an effect:

- If $t_i > t_{\text{crit}}(\alpha, v)$, the effect is significant.
- If $t_i < t_{\text{crit}}(\alpha, v)$, the effect is not significant.

Experimental variance

In order to estimate the common variance of the residuals, it is imperative to neglect at least one effect. Without this action, we cannot calculate the common variance of the residuals σ^2 for a complete plan $n = p$.

It will be useful to pass over the high-order interactions (3 or more) [24].

The estimator of the common variance of the residuals is given by the relation (8):

$$\sigma^2 = \frac{1}{n - p} \sum e_i^2 \quad (8)$$

Under these conditions, we can show that all the effects have the same variance given by the relation (9):

$$\sigma_i^2 = \frac{\sigma^2}{n} \quad (9)$$

We collect the residuals and the variances corresponding to each effect in Tab. 6:



Y _i estimated	e _i ²	σ _i
71.56	1.39	1.179
64.86	1.39	1.179
23.44	1.39	1.179
24.78	1.39	1.179
505.29	1.39	1.179
485.21	1.39	1.179
179.24	1.39	1.179
71.56	1.39	1.179

Table 6: Calculation of residuals and variances.

t _i	Results	Observation
t ₀ = 161.318 > 12.71	Significant	The effect of the constant (average) value is significant
t ₁ = 3.977 < 12.71	not Significant	The effect of Vibration amplitude (A) is not significant
t ₂ = 77.639 > 12.71	Significant	The effect of Tool rotation speed (S) is significant
t ₃ = 122.166 > 12.71	Significant	The effect of Feedrate (Fr) is significant
t ₁₂ = 1.702 < 12.71	not Significant	The effect of the interaction between Vibration amplitude (A) and Tool rotation speed (S) is not significant
t ₁₃ = 2.840 < 12.71	not Significant	The effect of the interaction between Vibration amplitude and the Feedraten is not significant
t ₂₃ = 58.937 > 12.71	Significant	The effect of the interaction between Tool rotation speed and Feedrate (Fr) is significant

Table 7: Signification of effects.

The calculation of the common variance of the residuals is given as follows:

$$\sigma^2 = \frac{1}{n-p} \sum e_i^2 = \frac{1}{8-7} (8 * 1.39) = 11.12$$

and the common variance of each effect:

$$\sigma_i^2 = \frac{\sigma^2}{n} = \frac{11.12}{8} = 1.39$$

The calculation of the Student test "t" for each effect is given as follows:

$$t_i = \frac{|a_i|}{\sigma_i}$$



The Student test table gives, for a risk of 5 % with $\nu = n - p = 8 - 7 = 1$ ddl :

$$t(\alpha; \nu) = t(0,05;1) = 12.706$$

where " t " is higher than 12.706. It is found that effect will therefore be significant with 5% risk. Tab. 7 is obtained: It is observed from Tab. 7 that the results are significant only with variables X2, X3 and the interaction I23. Therefore, we should retain a model of the following form:

$$y = 190.19 - 91.53X_2 + 144.03X_3 - 69.48I_{23}$$

$$F = 190.19 - 91.53S + 144.03F_r - 69.48S F_r$$

CONCLUSION

This research paper described the application of design of experiment based desirability analysis for parametric design of FSW process.

In order to show the influence of the three parameters studied and their effects on the Tensile strength for the FSW welding process according to the experimental plan method, we find a mathematical model which represents the analytical part of this optimization. Our optimization model allows us to better understand the process, the following outcomes were disclosed:

- The DOE technique was very convenient for predicting the parametric design of input process parameter;
- The influence of the parameters is quantified;
- This process improves the quality characteristics in term of the best output responses.
- The parameters are prioritized;
- The optimum welding condition found as rotation speed 1000 rpm, welding speed 90 (mm/min) and the round pin which takes the ratio (S_s / S_d) equal to 1 which mean the circular pin profile show a significant advantage compared to the square pin;
- Their direction of variation is known;
- Interactions are highlighted;
- The responses are modeled;
- The difference between the experimental response and the predicted (estimated) response were calculated taking into account the parameter of the prediction quality estimated equal to 0.996.

We can therefore conclude that the choice of the type of pin is very important in an FSW welding operation, the interaction of the latter with the rotation speed has more influence than the interaction with the welding speed, Knowing that the choice of the pin is the most influential (dominant) factor than the effect of the rotational speed and the welding speed.

The effect of the welding speed is less significant when the rotation speed takes on greater values and this is manifested in the slight slope.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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