A MODEL OF FRACTIONAL FACTORIAL DESIGN OF EXPERIMENTS IN AIRCRAFT COMPONENTS ENGINE

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Abstract. *This work aims at studying one component of the G.E. CF6-50 aircraft motor, named Seal (SARD) which it is located in the high-pressure turbine. The welding process employed for repairing this seal (which is made of inconel 718 alloy, a nickel-based alloy) was Dabber-TIG with pulsed wire. It was identified that the relevant answer parameters for the analysis were the height and the width of the fillet weld. In the identification of the welding optimal parameters, the two level fractional factorial statistical technique of experimental designs was used with 16 runs. It was identified that for the answer parameter height of the weld fillet the significant main effects are the welding speed, wire fire speed and welding current. For the answer parameter width of the fillet weld it was verified that the significant main effects were the welding current, the arc voltage and the welding speed.*

Keywords*: Dabber TIG repair welding, factorial experimental designs, inconel 718.*

1. Introduction

In the aeronautical industry, safety and quality related features are of almost importance. In this sense, material as well as component manufacturing processes are very expensive and complex, so that instead of disposing of aged or fractured components alternatives should be searched as for example, repair welding.

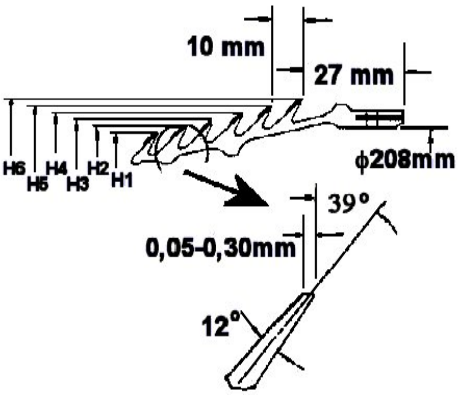
In aircraft engine GE C6-50, the forward rotating air seal which is located in the high-pressure turbine of the engine is employed for refrigerating the first and second stage fans of the high-pressure turbine. Implications of failures of this seal are discussed in Telecklenburg (1984), Alles (1985), Anderson (1985), Ballman (1985), Lopez (1990) and Fernandes (1997). This component was repaired by the welding process pulsed wire Dabber TIG, which has been developed and patented by the General Electric Co. The Dabber TIG welding with pulsed wire, that is, with continuous wire feeding (addition metal) allows uniformity of welding.

In a recent paper, Fernandes *et. al.* (2003) using a two level factorial experimental design with five variables (factors), makes a comparing in a total of 64 runs and identified the welding current (X_I), the electric arc voltage (X_V), the dabber or pulsing frequency (X_D), the wire feeding speed (X_A), and the welding speed (X_S) as the seal Dabber TIG repair welding optimal parameters. Also in this reference, the height and width of the welding arc were the relevant responses. The aim of this paper is to study the possibility of using fewer experiments than in Fernandes (1997, 2003). For this purpose, factorial experiments with 16 runs have been used for the same data obtained by Fernandes (2003).

2. Welding Repair Problem

The seal is manufactured by forging with the Inconnel 718 alloy is located in the high pressure turbine of the G.E. CF6-50 aircraft jet engine. In this engine, part of the air flux is employed for refrigerating it, for protecting the turbine blades and for the cabin pressurization. The remaining air flux must be sealed in order to avoid undesired losses. Seals are employed in order to trap greater air masses in the jet engine. These seals direct the air to those regions for which refrigerantion is needed. The seal studied in this paper has 6 knifes (Figure 1) which direct the air to refrigerate the blades of the first and second high-pressure turbine stages of the aircraft jet engine G.E. CF6-50, whose temperature is aproximately 900 ^{o}C (1,650 ^{o}F). The General Electric specifications for the minimal dimensions of the seal external diameters ($\varnothing_{ext}$) before and after the repair welding of its knifes are presented in Figure 1.

The seal works under 11,000 rotations per minute, a pressure of approximately 27.22 bar, and a temperature about 500°C (930°C). The seal wear-out takes place in its knifes due to the friction with the pressurized air passing between the rotating air seal and the stationary air seal. The seal wear-out, which is greater when an aircraft takes off, may lead to an engine failure under flight, thus endangering the aircraft safety. The excessive knife wear-out leads to the jet engine loss due to lack of adequate blade refrigeration, thus requiring the replacement of the entire failed package related to the high-pressure turbine.



	External Diameter (mm)	
	Before Welding	After Welding
H1	198,12	201,12 a 201,37
H2	202,18	205,97 a 206,22
H3	206,25	210,03 a 210,35
H4	210,31	214,10 a 214,35
H5	214,38	218,16 a 218,41
H6	218,44	222,22 a 222,48

Figure 1. Dimensions specified by the General Electric Co. for the forward rotating air seal of the G.E. CVF6-50 jet engine.

Jet engine parts are usually very expensive because they are made up of special metal alloys and also because they require special processes for being manufactured. This reason has lead to the development of welding repair techniques that fulfill high quality standards, involve low heat inputs and also induce the least number of distortions in the repaired part.

The welding repair of seals has been performed by means of the manual TIG procedure. The use of this procedure, however, has lead to irregular weld fillets and the repaired parts presented excessive distortions, which could lead to the welded part scrapping (Figure 2, left). Another welding repair trial has been performed by means of the MIG (Metal Inert Gas) welding procedure. However, in this case the seal knife sides often presented welding overlapping (Figure 2, right). Also, after being machined the seal knifes exhibited many cracks and lack of fusion between welding passes, a great heat affected zone and welding splashes, which turned it more difficult to machine them, for the knife pitch was very small.

The aforementioned features have led to the development of new welding techniques, like the TIG welding with pulsed wire, also known as the Dabber-TIG welding (Figure 2, left). This welding technique allows for reducing the repair time by a factor of 2, and also reduces the addition material and the thermal treatment after welding costs. The Dabber-TIG welding equipment used in this work costs about US$ 250,000.00. It has been developed and patented by the General Electric Co., being manufactured under license solely by the Hobart Brothers Company, Ohio, U.S.

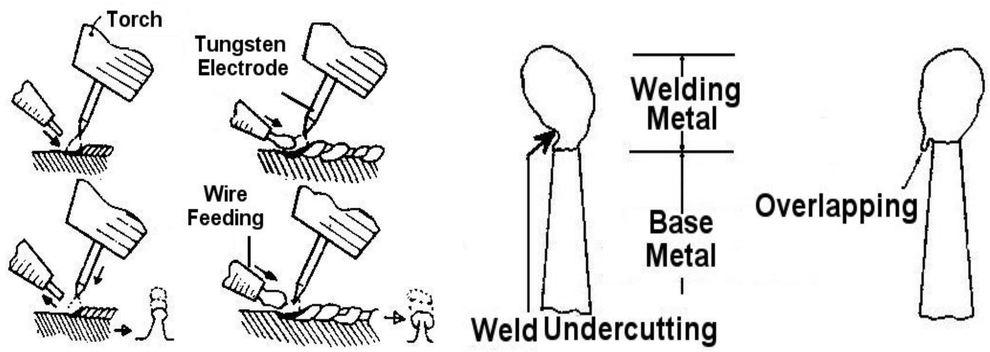


Figure 2. Addition material deposition pattern for the TIG welding procedure (left) and for the MIG procedure (right).

3. Methodology

According to Montgomery (1997) and Draper (1998), the definition and choice of any variables, as well as responses of the factorial experimental design to not belong to the statistical field, being related to the specialist. In this technique when one performs experiments, aims at studying the effect of one or more factors on a response variable. Each factor contributes by predefined amounts or categories named levels. Every combination of levels of the different factors is termed a combination of treatments. The set of combinations of treatments used determines the corresponding experimental design, which is termed a factorial experiment.

For the factorial experiment with two levels, when one analyses five parameters, the method is named 2^5. The method uses 32 treatment combinations for analyzing the parameters of interest. In the case each treatment combination be repeated r times, then the total number of tests will be 32*r. The assumed figures for these parameters are arranged in a table below of +1 or -1 entries, named Yates' matrix a fraction of which is shown in table 1. In this matrix, the signs –

and + mean the lower and upper limits of the independent variable for the variation range previously selected for the parameter under study (Fernandes, 2003).

According to Montgomery (1997), a fraction of the complete factorial experiment is named a fractional factorial design. In the case of the 2^5 factorial experiment with 32 runs the fraction of the complete experiment considered in this study is a fractional factorial experiment with 16 runs, with a V resolution, that is, a design that allows for estimating the overall mean, all the 5 main effects and all the 10 interactions of two factors, considering that the interaction of 3, 4, or 5 factors are negligible. The fractional design has been devised by considering all the treatment combinations of the complete experiment for which the product of the I*V*A*S*D column is equal to +1.

Table 1. Yates' matrix for a fractional factorial experimental design with two levels with 5 variables with 16 runs.

Nº	**Exp.**	**I**	**V**	**A**	**S**	**D**	**IVASD**	*Results*
1	i	+	-	-	-	-	+	y1
2	v	-	+	-	-	-	+	y2
3	a	-	-	+	-	-	+	y3
4	iva	+	+	+	-	-	+	y4
5	s	-	-	-	+	-	+	y5
6	ivs	+	+	-	+	-	+	y6
7	ias	+	-	+	+	-	+	y7
8	vas	-	+	+	+	+	+	y8
9	d	-	-	-	-	+	+	y9
10	ivd	+	+	-	-	+	+	y10
11	iad	+	-	+	-	+	+	y11
12	vad	-	+	+	-	+	+	y12
13	isd	+	-	-	+	+	+	y13
14	vsd	-	+	-	+	+	+	y14
15	asd	-	-	+	+	+	+	y15
16	ivasd	+	+	+	+	+	+	y16

Where **I, V, A, S, e D** represents, respectively, the main effects of current arc welding, the voltage arc welding, the wire feeding speed, the welding speed and the dabber or pulsing frequency. **IVASD** represents the interaction effect of the five factors above.

According to Drapper (1998), the 2^k factorial experiment may be expressed by equation 1, where $\hat{\mathbf{y}}$ is the estimated or fitted value for each response, $\hat{\boldsymbol{\beta}}_{\mathbf{o}}$ is the estimate of the overall model mean, $\hat{\boldsymbol{\beta}}_{\mathbf{i}}$ is half the estimate of the true main effect of the *i-th* factor and $\hat{\boldsymbol{\beta}}_{\mathbf{i,j..k}}$ is half the estimate for the true interaction effect of factors *i, j, ..., k*. It should be emphasized that the parameters of equation 1 are unknown, and so they should be estimated from the collected data.

$$\hat{\mathbf{y}} = \hat{\boldsymbol{\beta}}_{\mathbf{o}} + \left[\sum_{\mathbf{i=1}}^{\mathbf{k}} \hat{\boldsymbol{\beta}}_{\mathbf{i}} \mathbf{x}_{\mathbf{i}} + \sum_{\mathbf{i=1}}^{\mathbf{k}} \sum_{\mathbf{j=1}}^{\mathbf{k}} \hat{\boldsymbol{\beta}}_{\mathbf{ij}} \mathbf{x}_{\mathbf{i}} \mathbf{x}_{\mathbf{j}} + \ldots + \hat{\boldsymbol{\beta}}_{\mathbf{12 \ldots k}} \mathbf{x}_{\mathbf{1}} \mathbf{x}_{\mathbf{2}} \ldots \mathbf{x}_{\mathbf{k}} \right] \tag{1}$$

In this equation (1), x_i = -1 if the *i-th* factor is setting at its low level and x_i = + 1 if it is setting at its high level. $\hat{\boldsymbol{\varepsilon}} = \mathbf{y} - \hat{\mathbf{y}}$ stands for the difference between the observed and the fitted value, and is called the residual. If the effect of the i-th factor is not significant, then the α_i will be equal to zero. However, due to the experimental error, the estimate $\hat{\boldsymbol{\alpha}}_{\mathbf{i}}$ will not necessarily be equal to zero, it will take a small value, instead. A hypothesis test, like the F test of the analysis of variance (ANOVA), for instance, will allow for deciding with a slight error (5%, in general) whether $\hat{\boldsymbol{\beta}}_{\mathbf{i}}$ is significant, that is, that is to say, if the true main effect of the *i-th* factor is equal to zero or not. The significance of interactions effects is tested in analog way.

Figure 3 shows the plot that represents the Normal Probability Plot for the Residuals allows for detecting possible deviations from normality of the model. In all the experiments with 16 runs, all points should approximately stand near a straight line. The experiment analysis has been performed by means of the Daniel plot (1976). Figure 4 shows the Daniel Plot displays the factorial effects on a normal probability paper, in which the effects are shown on the horizontal axis and the expected normal value on the vertical axis. The basic idea is that the insignificant effects are not distinguished from the random error, and so will follow a normal distribution with zero mean and a variance equal to σ^2. On the normal probability plot, this corresponds to a set of points on a straight line. When one tests the null hypothesis, that is, the hypothesis of negligible factorial effects, the insignificant effects are considered to be zero while the significant ones are those whose absolute values are much greater than zero. In this sense, the significant effects will be those that are far from the straight line (Daniel, 1976; Soong, 1981, Montgomery, 1997).

For validation of ANOVA, the errors are independent and Gaussian (normality) shape distributed with average zero and constant variance σ^2. The verification of those suppositions is made through the analysis of the residues of the models by the Normal Probability Plot of the residues that allows verifying the condition of normality of the mistakes.

Figure 5 shows the predicted versus residual values and allows to analyze possible deviations of the supposition of constant variance for the model. For the case in study, figure 5 displays a variance situation approximately constant, that is, the variance doesn't increase and decrease, when the adjusted values increase.

4. Results and Discussion

Experiments have been devised for identifying the range of the welding parameters for the Dabber TIG welding procedure, that is, which allow for obtaining an appropriate seal knife (in terms of the height and width of the weld fillet) and free from defects (liquation hot tears, aging cracks, tungsten inclusion, overlap, etc.). These ranges for the welding parameters, shown in table 2, allow for and optimal reduction of the height and width of the weld fillet, as well as its number of welding passes.

The Statistica 6.0® software has been employed for analyzing how the Dabber TIG welding parameters influenced the height and width of the repair weld fillet. Figure 3 displays the normal probability plots of the residues for the experiment with 16 runs. Acure deviations from normality have been observed. Figures 4 displays the Daniel plots, which show the significant factorial effects for the height and width of the weld fillet, by considering 16 runs.

Table 2. Ranges for the optimal welding parameters for the Dabber TIG Procedure.

Symbols	Welding Parameters	Highest Value (+)	Lowest Value (-)
I	Welding current [A]	21,00	14,00
V	Electric arc voltage [V]	11,20	9,50
S	Welding speed [mm/s]	1,23	1,19
A	Wire feeding speed [mm/s]	2,32	1,40
D	Wire pulsating frequency [pps]	2,12	1,23

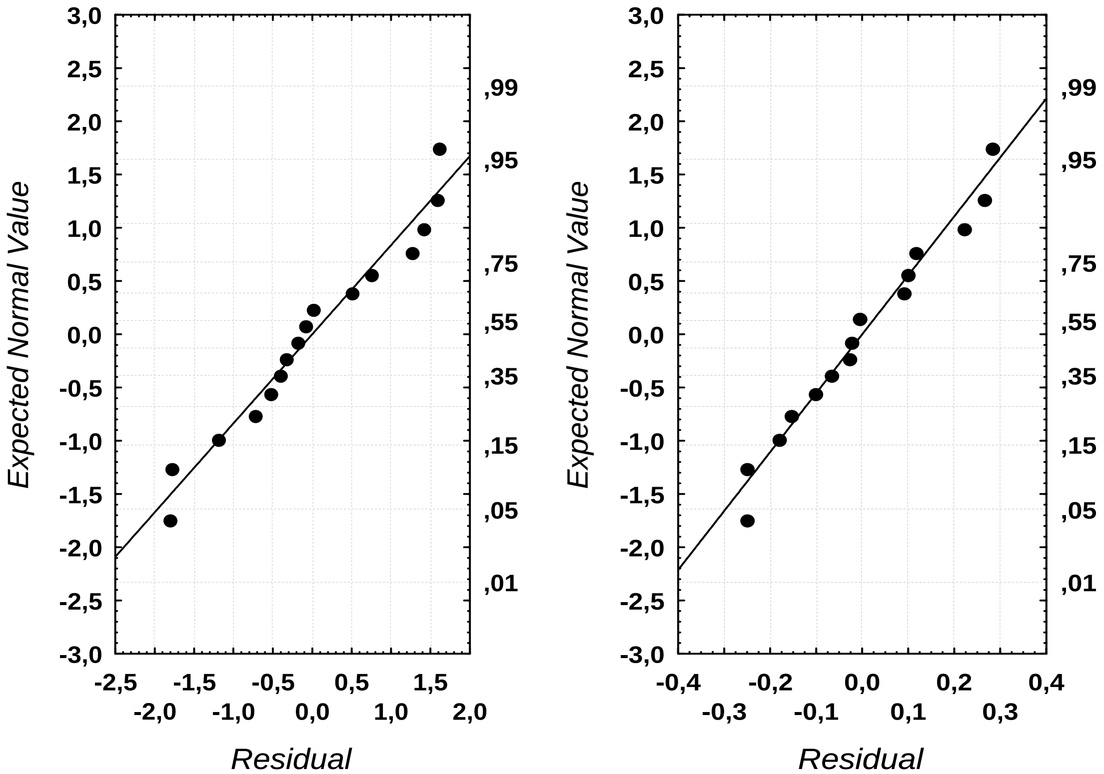


Figure 3. Normal probability plotting of the height (a) and width (b) responses for the weld fillet.

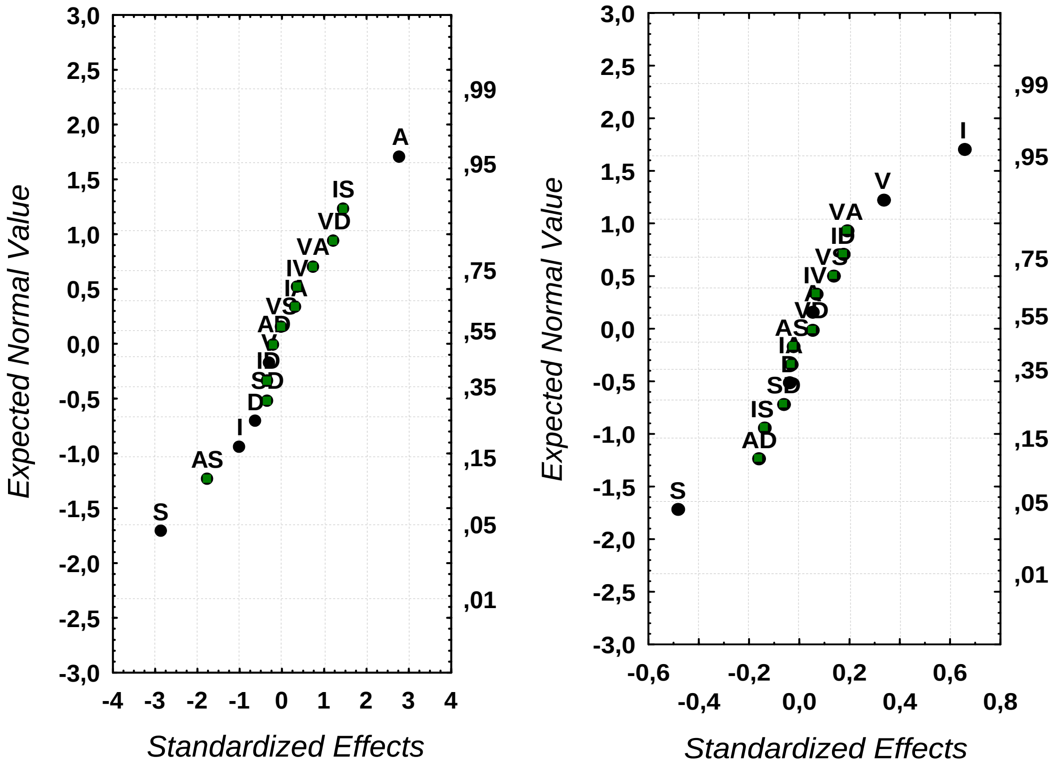


Figure 4. Normal probability plotting for the factorial effects considering 16 tests for the height (a) and width (b) of the weld fillet.

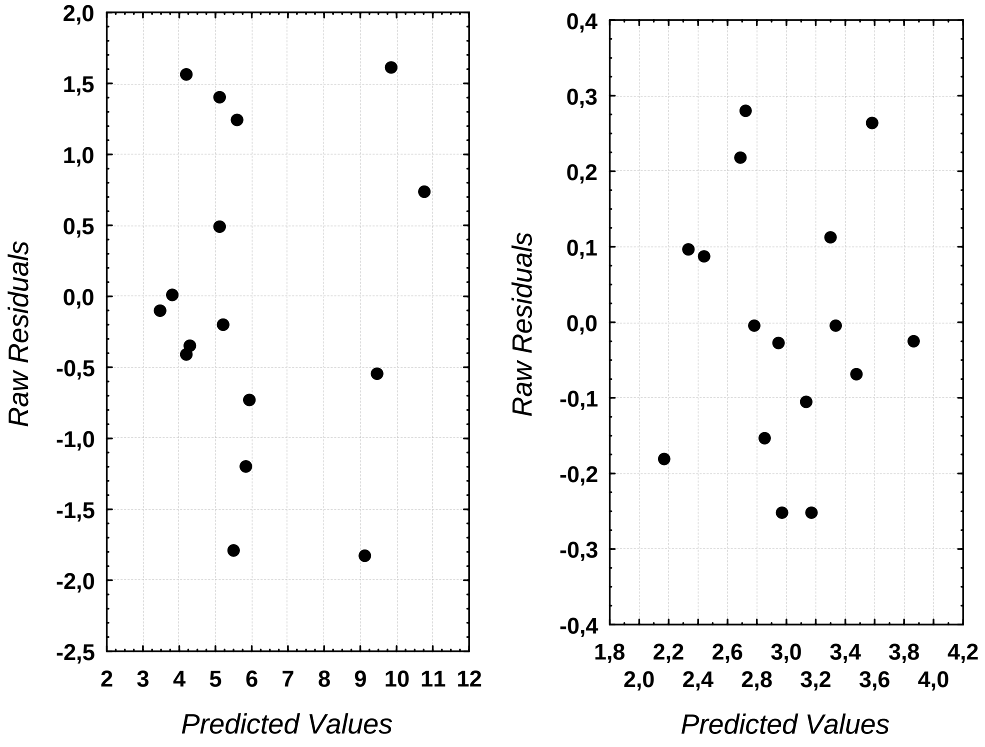


Figure 5. Predicted versus residuals values plotting for the factorial effects considering 16 tests for the height (a) and width (b) of the weld fillet.

Table 3 shows the fitting of the models obtained from the factorial design experimentation for the height and width of the weld fillet, fitted to the normal density function. This table considers the factorial design for 16 runs, so that the main significant effects are displayed in descending order of relevance.

Table 3. Factorial design models for the height and width responses of the weld fillet considering 16 runs.

Numbers of Runs	Models
16 runs	$\hat{\mathbf{Y}}_{\mathbf{HEIGHT}} = \mathbf{6{,}07 - 1{,}43X_S + 1{,}39X_A - 0{,}50X_I - 0{,}89X_A X_S}$
	$\hat{\mathbf{Y}}_{\mathbf{WIDTH}} = \mathbf{2{,}98 + 0{,}32X_I - 0{,}24X_S + 0{,}16X_V + 0{,}09X_I X_D}$

It could be observed, in table 3, for the height of weld fillet, the sign of effect X_A is positive while the signs of X_S, X_I and X_AX_S are negative. This means that the height of fillet weld increases when X_A passes of a low level (1,40 mm/s) for the high level (2,32 mm/s). The negative sign of X_I shows the height of the fillet weld decreases when the current is increased from 14A to 21A. Similarly, the X_S reduces the height of fillet weld when X_S increases of 1,19 mm/s for 1,23 mm/s. However the analysis of the negative sign of the interaction is not so simple. As the width concerns the effect of X_I is positive showing that the width is increased when the current is increased from 14,0 A to 21,0 A. The effect of X_V is also positive, in other words, the increase of the voltage determines an increase of the width of the fillet weld. The sign of X_S is negative showing that an increase of the welding speed (X_S), implicates in a decrease of the width of weld fillet. The constants values show in table 3, corresponds results that would be obtained for the case that in the there were significant effects.

Tables 4 and 5, shows the analysis of variances (ANOVA) for the height and width of the of the weld fillet, respectively. In these tables it can be defined the values of **SS** as being the sum of squares of the factorial effects; **df** the number of degrees of freedom; **MS** the medium square; **MSe** that has the value 2,05383, of the Medium Square of the error and **F = MS / Mse**. Very small values of **p** (for instance $\leq 0{,}05$) they are an indication of a significant effect. The p-value, also named “critical level” is the least significance level to reject the null hypothesis with the found F-value. It is read from the Snedecor-F distribution.

Table 4. Table of the analyses de variance (ANOVA) for the height responses of the weld fillet considering 16 runs.

Factor	SS	Df	MS	F	p
I	4,0000	1	4,0000	1,9476	0,1963
V	0,3600	1	0,3600	0,1753	0,6853
A	**31,0806**	**1**	**31,0806**	**15,1330**	**0,0037**
S	**32,8902**	**1**	**32,8902**	**16,0141**	**0,0031**
D	1,6256	1	1,6256	0,7915	0,3968
AS	**12,5670**	**1**	**12,5670**	**6,1188**	**0,0354**
Error	18,4845	9	2,0538		
Total SS	101,0080	15			

Table 5. Table of the analyses de variance (ANOVA) for the width responses of the weld fillet considering 16 runs.

Factor	SS	Df	MS	F	p
I	**1,7096**	**1**	**1,7096**	**36,0957**	**0,0002**
V	**0,4456**	**1**	**0,4456**	**9,4075**	**0,0134**
A	0,0116	1	0,0116	0,2440	0,6332
S	**0,9264**	**1**	**0,9264**	**19,5602**	**0,0017**
D	0,0060	1	0,0060	0,1268	0,7300
VA	0,1388	1	0,1388	2,9297	0,1211
Error	0,4263	9	0,0474		
Total SS	3,6641	15			

Tables 4 and 5 are verified that the significant effects for height of the solder string the significant effects are X_A, X_S e a interaction X_{AS}. Already for the width of the solder string the significant effects are X_I, X_S e a interaction X_{VA}. Figure 3 shows the graphs of the values adjusted versus the residual values, for the height (fig. 3a) and for the width of the solder string (fig. 3b). In these figures the variance situation can be evaluated approximately constant, that is, was neither verified increase nor decrease of the adjusted values, so much for the height as for the width of the soldability.

5. Conclusions

The repair welding of the forward rotating air seal knife of the CF6-50 jet engine, made of inconel 718 alloy, performed by means of the Dabber TIG process with pulsating wire and employing the two-level factorial experimental design technique allowed for observing that the most influential welding parameters for the weld fillet height were the welding current (X_I), the welding speed (X_s), the wire feeding speed (X_A) and the interaction between the welding speed and the wire feeding speed ($X_A.X_S$). For the weld fillet width, the most relevant parameters were the welding current (X_I), the welding speed (X_s), and the interaction between the welding current and the wire pulsation ($X_I.X_D$). It has also been verified that the experiment with 16 tests presents results close to those displayed in Fernandes *et al.* (2003), in which higher number of tests were used.

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