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Research Article

Designing experiments to study welding processes: using the Taguchi method

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Abstract

Identification of significant process parameters using experiments needs to be carefully formulated as it can be a resource demanding process. Using appropriate statistical techniques such as the Taguchi method of factorial design of experiments, the number of necessary experiments can be reduced and the statistical significance of parameters can be safely identified. In the case of linear friction welding it was found that the frequency of oscillation, power input and forging pressure are statistically insignificant for the range of friction pressures studied.

Keywords: taguchi method, factorial design of experiments, friction welding.

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1. Introduction

An experiment can be considered as a process seeking to answer one or more carefully formulated questions. It should have carefully described goals which will be used to choose the appropriate factors and their range, as well as the relevant procedure. The factors studied should not be covered by other variables, with the chosen experimental sequence removing the effects of the uncontrolled variables. Replication of the experiments will help to randomise the results taken, to limit bias from the experiments. While replication ensures a measure of precision, randomisation provides validity of the measure of precision. By using this technique, many evaluations are usually needed to get sufficient information which can be a time-consuming process.

The term "design of experiments" was originated around 1920 by Ronald A. Fisher, a British scientist who studied and proposed a more systematic approach in order to maximize the knowledge gained from experimental data [1] nce then, design of experiments has become an important methodology that maximizes the knowledge gained from experimental data by using a smart positioning of points in the space. This methodology provides a strong tool to design and analyze experiments; it eliminates redundant observations and reduces the time and resources to make experiments.

In general, we can say that a good distribution of points achieved through a DOE (design of experiments) technique will extract as much information as possible from a system, based on as few data points as possible. Ideally, a set of points made with an appropriate DOE should have a good distribution of input parameter configurations. This equates to having a low correlation between inputs. The DOE approach is important to determine the behavior of the objective function we are examining because it is able to identify which factors are more important. The choice of DOE depends mainly on the type of objectives and on the number of variables involved. Usually, only linear or quadratic relations are detected. However and fortunately, higher-order interactions are rarely important and for most purposes it is only necessary to evaluate the main effects of each variable. This can be done with just a fraction of the runs, using only a "high" and "low" setting for each factor and some center points when necessary.

Therefore DOE statistical techniques are especially useful in complex physical processes, such as welding. These processes usually involve a large number of interrelating parameters, which range from applied pressure to operating temperature and material properties, that are related with complex laws not fully described to the extent necessary for successful industrial implementation of such processes.

2. Friction Welding Experiments

Linear friction welding is a solid state process for joining materials either metals or plastics together [Fig.1] through intimate contact of a plasticised interface, which is generated by frictional heat produced as one component is moved under pressure in a direct reciprocating mode relative to another.

The process is observed to have four distinct phases, which have been previously described [2] in some detail, and are discussed only briefly here for completeness.

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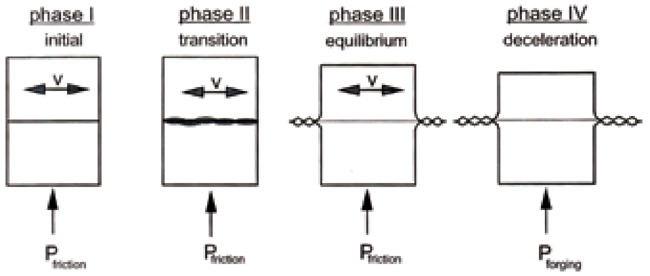


Figure 1. Schematic depiction of the four distinct phases that are incorporated in the linear friction welding process.

Phase I, The Initial Phase. From the initial phase the two workpieces are moving under pressure in a linear reciprocating manner. Heat is generated from solid friction, with the friction coefficient between the oscillating workpieces not exceeding unity, but increasing throughout this phase. True surface contact area increases throughout this phase due to wear and the thermal softening effects of movement. No weld penetration is experienced at this stage. This phase is critical for the rest of process to proceed, for if insufficient heat is generated the next phase will not follow.

Phase II, The Transition Phase. Large wear particles are expelled from the rubbing interface. The heat affected zone expands from the asperities into the bulk of the material until phase III is reached. The true contact area is considered to be 100% of the cross sectional area, and the plasticised layer formed between the two rubbing surfaces cannot support the axial load, thus deforming permanently.

Macroscopically, under the naked eye, in certain materials such as Ti6Al4V (numbers indicate wt.%), red hot spots appear at the interface, that extend with time till they cover the whole of the rubbing interface, and are accompanied by an exothermic reaction with oxygen.

Phase III, The Equilibrium Phase. Axial shortening begins to register as plasticised matter is expelled into the upset. Material in the heat affected zone that has yielded, from the friction pressure exerted on it and the high temperature reached, moves out of the rubbing interface aided by the oscillatory movement. This form a flash, which may take different shape depending on the material extruded. The material never reaches melting conditions at the interface, as experimental data have shown. But even, if such temperatures were reached, the molten material would have been expelled out of the interface from the friction pressure with the aid of the workpiece movement, as molten material cannot withstand any load.

Macroscopically, under the naked eye, in certain materials such as Ti6Al4V, as was observed by the author in all the experiments performed with this material [3], there is an exothermic reaction with oxygen. In the case of Ti6Al4V which is studied in this paper, the extruded material from the two specimens forms a single joined flash, and not separate flashes for each specimen [4]. This indicates that the plastic material at the rubbing interface has been joined together at this stage.

Phase IV, The Deceleration Phase. When the desired upset is reached the two materials are brought to rest very rapidly (in less than 0.1 s), and forging pressure may be applied. This last phase is thought of importance by specialists in the friction welding industry, and is used to consolidate the weld.

From the foregoing description it is evident that there is a power input limit, below which welding is not possible. If operating below this limit, either by using smaller amplitude of oscillation or rubbing at a lower frequency of oscillation or applying a smaller friction pressure than necessary, the workpieces will never reach conditions which will produce well defined flash and subsequently join to form sound welds.

Linear friction welding is a joining process aimed at extending the current applications for rotary friction welding to non axisymmetric metal and plastic components. However, the two processes differ considerably in the mode of heat input and the stress field imposed on the plasticized layer, and therefore existing rotary friction welding models are not directly applicable to linear friction welding. The more uniform interfacial energy generation present in linear friction welding may account for higher integrity welds. Moreover, much of the research in rotary friction welding is of an empirical nature, which cannot be used to predict weldability and optimum welding parameters for new materials with linear friction welding.

3. Designing Experiments

In the parametric design of the experiments the fractional factorial method [5] is used to assess the effect of a number of factors on the impact strength of linear friction welding of Ti6Al4V joints. If the full factorial experiment method was used four experiments plus replications would be required. The fractional factorial experimental design enables the reduction of the number of experiments using an adequately chosen fraction of the treatment combinations required for the complete factorial experiment, and the study of the combined effect of individual factors. The combined effect of the individual factors has to be less material than that of the main factors. Therefore, some understanding of the influence of both the main factors and the interactive factors is required for aliasing to be carried out. To avoid invalid results, the interactive effect should not be connected with less significant main effects.

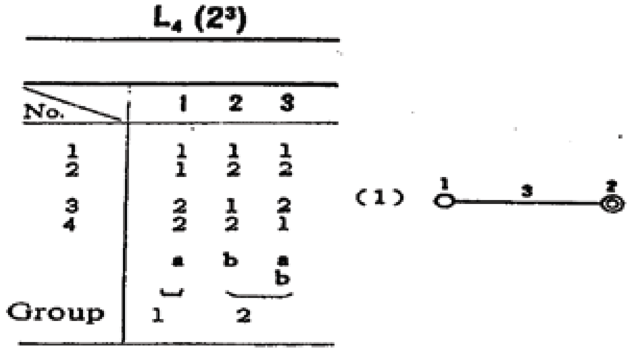
In designing a fractional factorial experiment care must be given so that all factors have an undeviating weight on other factors, at all levels that the may take, and orthogonal arrays [6] [7] [8] [9] are used to that effect. In these arrays, each factor is equally influenced by the effects of the factors under study.

In [5] a number of orthogonal arrays are given for different experiments, and a L4 array is shown [Fig.2]. The first row indicates the number of factors which will be tested, which are 3 in this case. The first column shows the number of experiments that must be completed for the fractional factorial experiment, in this case being four. The other columns underneath show the levels of each factor. In the first experiment of this array all factors are set to level 1, and similarly for the other rows.

Each factor in an orthogonal array has a degree of freedom associated with it, which prescribes the orthogonal array selected. The degree of freedom of each factor is equal to the levels that it takes minus one. For an interaction factor, the degree of freedom is equal to the product of the degrees of freedom of the factors that compose it.

The sum of the degrees of freedom of each individual factor studied must be equal, at the most, to the degree of freedom of the orthogonal array. The degree of freedom of the array is equal to the number of experiments performed minus one.

To study the interaction between factors, the orthogonal array can be used to include this interaction as a separate factor. The number of factors under investigation will have to be reduced, so as to retain the correct number of degrees of freedom. A linear graph [Fig.2] is used to maintain the orthogonality in the array. It corresponds to columns in the orthogonal array, and on each line the factors investigated for association are shown. For example column 3 is reserved for the interaction between factors 1 and 2.



$L_4 (2^3)$

No.	1	2	3
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1
	a	b	a b
Group	1	2	

Figure 2. L_4 Orthogonal array used for fractional factorial experimental designs and linear graph to manipulate it [5].

4. Analysis of Designed Experiments

Once linear friction welding experiments with Ti6Al4V have been completed [Table 1], results are analysed by calculating the signal-to-noise (S/N) ratio for each factor and each level in these experiments. This ratio is the reciprocal of the variance of the measurement error which is maximal for the combination of parameter levels that has the minimum error variance. Calculating the average of S/N value for each factor and plotting them for each level reveals the effect of the factor on the variable used to assess these experiments. In addition, analysis of variance (ANOVA) techniques can be used to study the fractional factorial experiments and identify the significance of each factor.

The linear friction welding process is controlled by a number of parameters such as the frequency of oscillation, the amplitude of oscillation and friction pressure [2]. These parameters directly affect the energy input into the process as the frictional heat that is generated by the oscillating process is directly related to these as physics laws dictate. Therefore, a joint may be produced depending on the values of the parameters used, with its weld strength affected by these as well as the forging force applied at the end of the process.

The variable used to assess the linear friction welding experiments in this investigation was the impact strength of the produced joint using a Charpy impact test, as the objective was to create joints which would have high value of impact strength. The Charpy impact test is a standardized high strain-rate test which determines the amount of energy absorbed by a notched material during fracture. This absorbed energy is an estimate of the material's or the joint's toughness. It is a widely used test by industtry. Friction welding produces joints whose tensile strength is almost equal to that of the parent material.

Joints produced were assessed using the Charpy impact test on an Avery impact test machine. The apparatus consists of a pendulum axe swinging at a notched sample of the welded joint. The energy transferred to the specimen can be inferred by comparing the difference in the height of the hammer before and after a big fracture. The notch in the specimen needs to be of regular dimensions and geometry.

A measure of experimental error is necessary to estimate the significance of the results. In large factorial experiments estimates of higher order interactions can be obtained. These estimates are actually estimates of experimental error, as it is assumed that higher order interactions are physically impossible. In small factorial designs, as in the one used here, there are no estimates of higher order interactions, and the estimate is based on past experience.

The analysis of these experiments of linear friction welding of Ti6Al4V are valid for the material studied and the operating range of the process parameters studied. Different materials will probably produce different results and demonstrate different parameter sensitivities. In addition to this complication, it may be possible that process parameters outside the envelope used in this experimental design may show different parameter sensitivities, although care has been taken to ensure that this possibility is at a minimum.

5. Parametric Investigation

Using the Taguchi method of designing fractional factorial experiments, the effects of these parameters were explored using two orthogonal L_4 arrays. The effect of the individual parameters is studied, as well as the combined effect that may have on the strength of the weld. The L_4 array is used in these designed experiments where two factors are changed to two levels each. Although in this case this design does not reduce the number of experiments performed, it should identify any statistically significant factors and distinguish any combined effect of them on the process. Analysis of the results indicates the effect of every factor on the parameter used for assessment and the effect of the combined interaction of the two factors as well. All experiments were repeated as it is common practice for justification of results. Once experiments have been completed, results are analysed by calculating the signal-to-noise (S/N) ratio for each factor and each level in these experiments. Calculating the average of S/N value for each factor and plotting them for each level reveals the effect of the factor on the variable used to assess these experiments.

5.1 Effect of frequency of oscillation and friction pressure

At a constant amplitude of oscillation of 0.92 mm, eight linear friction welds of Ti 6Al 4V were produced at a frequency of oscillation of 50 and 100 Hz, and at two friction pressures of 32 and 39 MPa [Table 1]. As the mechanism to apply the friction pressure produced a varying pressure during the process, the friction pressure value used was the one achieved at the end of the process, as it is more representative of the conditions that exist at the end of the process and could govern the impact strength of the joint. The initial friction pressures applied were higher, by such an amount as to take into account the reduction in frictional force due to axial shortening that would be produced during the subsequent run.

Analysing the results [Table 2] showed that the parameters studied in this experiment, i.e. frequency of oscillation and friction pressure, were not statistically significant, as their variance ratio was below 2. As expected, the combined effect does not affect the weld integrity as well. Increasing the friction pressure produced no statistically stronger welds. It should be noted that the range of the friction pressures used in this set of designed experiments was limited by the operational characteristics of the linear friction welding rig.

Table 1. Experimental design used to investigate the parameters of frequency of oscillation and friction pressure (α : 0.92 mm)

	f (Hz)	**Final P_{fr} (MPa)**	**S/N Value (db)**
1	50	32	8.15
2	50	39	7.82
3	100	32	8.00
4	100	39	7.88

A large number of experiments performed later, following a wide range of functional improvements made on the welding rig, where the full allowable range of friction pressure was used, showed an effect of friction pressure on the impact strength of the joints. This emphasizes the need to select an appropriately wide range of parameters for the analysis to be representative of the process. These experiments are not included in this work as the aim of this paper is to demonstrate the use of fractional factorial experiments and not list an extensive list of experimental data.

Table 2. Analysis of variance of S/N data showing significance of frequency of oscillation and friction pressure on the impact strength of linear friction welds of Ti 6Al 4V

	Degrees of Freedom	**Sum of Squares**	**Variance**
(A) Frequency of Oscillation	1	0.0026	0.0026
(B) Friction Pressure	1	0.051	0.051
(A)X(B) Interaction	1	0.011	0.011

5.2 Effect of power input and forging pressure

Power input and the forging pressure applied at the end of process were examined using the same orthogonal array as before, at an amplitude of oscillation of 3 mm. The power input parameter was changed by altering the friction pressure, and the forging pressure was investigated at two levels, one the same as the final friction pressure and the other at 80 MPa [Table 3]. The low level of forging force, was effected by not applying an additional further pressure at the end of the process, but leaving the welded specimens in the chucks under the friction pressure.

As it can be seen [Table 4] the specific power input parameter, the forging pressure as well the combined interaction between the two parameters as their variance is below 2. It should be noted that the range of the friction pressures used was limited by the operational characteristics of the rig and the design of experiment procedure. As stated earlier, experimental results where the full allowable range of friction pressure was used showed the significant effect of friction pressure [3].

Table 3. Experimental design used to investigate the parameters of power input parameter and forging pressure (α : 3 mm)

	Power Input Parameter	**Forging Pressure (MPa)**	**S/N Value (db)**
1	939	0	8.04
2	951	80	8.05
3	1122	0	8.16
4	1092	80	8.18

Table 4. Analysis of variance of S/N data showing significance of power input parameter and forging pressure on the impact strength of linear friction welds of Ti 6Al 4V

	Degrees of Freedom	**Sum of Squares**	**Variance**
(A) Power Input Parameter	1	0.015	0.015
(B) Forging Pressure	1	3E-4	3E-4
(A)X(B) Interaction	1	1E-6	1E-6

6. Conclusions

A number of linear friction welding of Ti6Al4V parameters were studied using the Taguchi method of designing fractional factorial experiments to identify their significance. It was found that:

- The frequency of oscillation and friction pressure were not statistically significant for the range of friction pressures studied.
- Power input to the joint and forging pressure were not statistically significant either.

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References

1. R. Fisher, The design of experiments, Oliver-Boyd, Edinburgh (1935).
2. A. Vairis, M. Frost, Wear 217, 117 (1998).
3. A. Vairis, PhD thesis, University of Bristol (1997).
4. A. Vairis, M. Frost, Mat. Sci. Eng. A 271, 477 (1999).
5. G. Taguchi, Introduction to quality engineering, Asian Productivity Organisation, Tokyo (1986).
6. A.S. Hedayat, N.J.A. Sloane, J. Stufken, Orthogonal Arrays, Theory and Applications, Springer-Verlang, New York (1999).
7. D.De Cock, J. Stufken, Stat. Probabil. Lett. 50, 383 (2000).
8. W.S. Diestelkamp, Design Code Cryptogr 33, 187 (2004).
9. Y. Zhang, Discrete Math. 307, 246 (2007).