OPTIMIZING THE PROCESS PARAMETERS OF DIFFUSION BONDED JOINTS OF TI-6AL-4V AND SS304

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Abstract

Titanium alloys are joined with stainless steels for applications in aerospace engines. The main purpose of the present study is to investigate the characteristics of dissimilar joining of Ti-6Al-4V with SS304 stainless steels using diffusion bonding process. For the diffusion bonding, temperature, pressure and holding time are the key parameters. The study will also investigate the suitability of ultrasonic C-scan, a non-destructive testing method for diffusion bonded joints; the characterization tests include ultrasonic C-scan analysis. Diffusion bonding experiments were carried out by varying the temperature from 750° C to 850° C, Pressure from 5 to 15 MPa and holding time from 60 to 120 min. Mechanical properties like tensile strength is investigated with respect to various process parameters. In order to minimize the energy consumption process parameters are optimized using L9 orthogonal array. The results of ultrasonic C-scan analyses on diffusion bonded joints of the two material combinations are in good correlation with their joint efficiency. The results of SEM-EDS analyzes on diffusion bonded joints of the two material combinations are in good correlation with the tensile test carried out at their joint interface.

Keywords: Diffusion bonding, Energy, Optimization, Titanium, SS304.

1. Introduction

Titanium alloys and stainless steels are becoming more popular as structural materials in the aerospace, nuclear, chemical and shipbuilding industries due to their exceptional corrosion resistance, high specific strengths, high toughness, low thermal conductivity and low density [1–6]. There is considerable interest in joining titanium to steel to reduce the cost for those stainless steels is an inexpensive material in most industrial fields [7]. However the conventional fusion welding methods are not feasible for the joining of Titanium and medium carbon steel because of their metallurgical incompatibility. As titanium alloy is chemically reactive and can easily pick up nitrogen and oxygen from the atmosphere, it is very difficult to obtain defect free bonding [8]. Therefore the welding of Titanium and stainless steel materials by the fusion welding method is very difficult. It has been found that high precision titanium alloy and carbon steel joints with good properties can be achieved by diffusion bonding [9]. Since it is an time consuming bonding process it is very much essential to optimize the process parameters like bonding temperature, bonding pressure and holding time so as to minimize the energy consumption without compromising mechanical properties of joints.

2. Experimental Work

The chemical compositions of Ti-6Al-4V and SS304 stainless steels are given in Table 1 and 2. The specimens were machined to dimensions of 40 mm diameter x 20 mm length. The bonding surfaces of samples were ground flat by 200#, 400# and 600# grit SiC papers and cleaned in acetone prior to diffusion bonding [11]. Then the polished and chemically treated specimens were stacked in a die made up of 316L stainless steel and the entire diffusion bonding setup was inserted into a vacuum chamber. The specimens were heated up to the bonding temperature using induction furnace with a heating rate of 25° C/min; simultaneously the required pressure was applied. After the completion of bonding, the samples were cooled to room temperature before removal from the chamber. By this procedure, 9 joints were fabricated using different combinations of bonding temperature, bonding pressure and holding time which is obtained from Taguchi L9 orthogonal array.

Table 1. Chemical composition of Ti-6Al-4V

Alloys	Sn	Mo	Fe	V	Ti	Al	Si
Ti-6Al-4V	0.018	0.015	0.584	3.43	90.66	4.845	0.322

Table 2. Chemical composition of SS304

Alloys	Mo	Cu	Ni	Fe	Mn	Cr	V	Al	P	Sn
SS304	0.2	0.448	0.602	81.1	0.011	17.5	1.16	0.08	0.05	0.015

During bonding of materials, energy consumption was noted with help of energy meter connected with the diffusion bonding machine. The fabricated joints were subject to wire cut EDM process and tested to identify the ultimate tensile strength of the joints.

3. Experimental Design

Taguchi method, a powerful tool for parameter design of performance characteristics, was used to determine optimal machining parameters for minimum energy consumption and to maximize the tensile strength. Taguchi proposed to acquire the characteristic data by using orthogonal arrays, and to analyze the performance measure from the data to decide the optimal process parameters. This method uses a special design of orthogonal arrays to study the entire parameter space with small number of experiments only, according to the Taguchi quality design concept, there are three categories of performance characteristics in the analysis of the S/N ratio: the lower-the better, the higher-the-better, and the nominal-the better. A larger S/N ratio corresponds to better performance characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. Also, a statistical analysis of variance (ANOVA) is performed to identify the process parameters that are statistically significant. The lower the better criterion for the energy consumption was selected for obtaining optimum for diffusion bonding characteristics. For lower the better criteria, S/N ratio values corresponding to the experimental values of energy consumption was calculated using the below equation.

$$\varphi = -10log\left[\frac{1}{N\sum_{n}^{i=1} y_i}\right]$$

For larger the better criteria, S/N ratio values corresponding to the experimental values of energy consumption was calculated using the below equation.

$$\varphi = -10log\left[\frac{1}{N\sum_{n}^{i=1} y_i^2}\right]$$

3.1. Design of Experiments (DOE) and Process Parameters

The DOE help for conducting experiments in a more systematic way. The process parameters with their levels are specified in Table 3 below. It shows three parameters, bonding temperature (T), bonding pressure (P), and holding time (H) with three levels for each factor.

Table 3. Experimental Factors and their Levels

Factor	Unit	Level 1	Level 2	Level 3
Temperature (T)	°C	750	800	850
Pressure (P)	MPa	5	10	15
Holding Time (t)	Minutes	60	90	120

3.2. Orthogonal Array (OA)

Orthogonal array allows for the maximum number of main effects to be estimated in an orthogonal manner, with minimum number of runs in experiment, L9 orthogonal array used in the study as presented in Table 4. Tensile strength and energy consumption of the diffusion bonded joints are represented by TS and EC respectively. These responses are function of bonding temperature (T), bonding pressure (P), and holding time (H).

Table 4. Experimental results

Temperature ˚c	Pressure Mpa	Holding time min	Tensile strength Mpa	Energy (Watt)
750	5	60	69	6.6
750	10	90	84	8
750	15	120	102	9.3
800	5	90	89	8.6
800	10	120	136	9.6
800	15	60	121	7.5
850	5	120	180	10.5
850	10	60	163	7.7
850	15	90	227	8.1

4. Results and Discussions

Nine experiments were successfully conducted based on Taguchi method. The experimental results for the energy consumption and Tensile strength are listed in Table 4. Typically, small values of Energy consumption and large values of tensile strength are desirable for good quality and accuracy in the bonding operation. Thus, the data sequences have a “smaller- the-better characteristic" for energy consumption and larger - the-better characteristic" for tensile strength.

4.1. Analysis of Mean (ANOM)

In ANOM, mean value of the S/N ratio at each level of the process parameters is computed by taking arithmetic mean average of S/N ratio at the selected level. Table 5 & 6 lists the ANOM results and the Fig. 1 and Fig.2 shows mean S/N graph for energy consumption and tensile strength respectively.

Table 5. Analysis of Mean (ANOM) – Energy consumption

Level	Temperature (T)	Pressure (P)	Time (t)
1	17.94	18.50	17.21
2	18.61	18.48	18.31
3	18.77	18.35	19.81
Delta	0.83	0.15	2.61
Rank	2	3	1

Table 6. Analysis of Mean (ANOM) – Tensile strength

Level	Temperature (T)	Pressure (P)	Time (t)
1	38.48	40.29	40.89
2	41.10	41.80	41.53
3	45.49	42.98	42.65
Delta	7.01	2.69	1.76
Rank	1	2	3

The combination of bonding parameters $T_1B_1t_1$ is found to be optimum to minimize energy consumption and $T_3B_3t_3$ is found to be optimum to maximize the tensile strength. Hence, Taguchi method optimizes the parameters not only those available in the selected design but it optimize from all possible combinations.

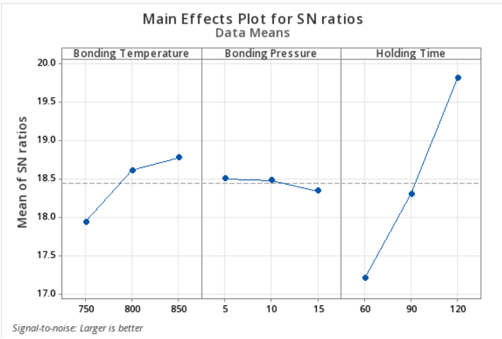

Fig. 1. Mean S/N Graph - Energy

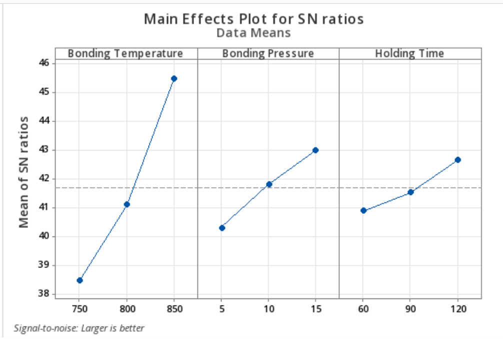

Fig. 2. Mean S/N Graph – Tensile strength

4.2. ANOVA

Normal probability plot (Fig. 3 & 4) was obtained to ensure that the data is normally distributed. It can be seen from Fig. 3 &4 that the data points either lie on the straight line or are close to it which validates the normality distribution of the measured data. The purpose of ANOVA experiments is to reduce and control the variation of process, so the decisions can be made concerning which parameter affect the performance of the process. ANOVA is a statistical method used to interpret the experimental data to take necessary decisions.

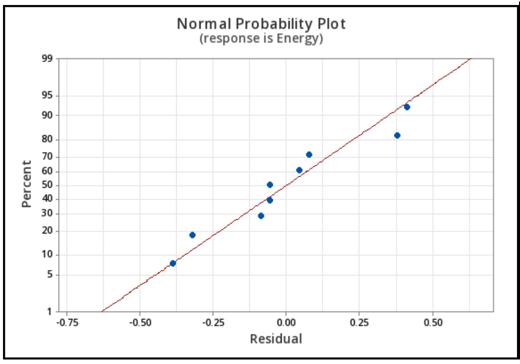

Fig. 3. Normal Probability plot - Energy

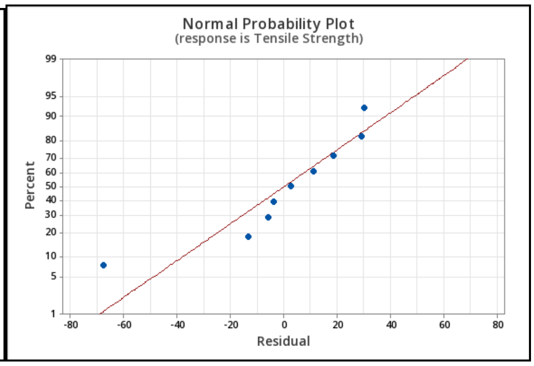

Fig. 4. Normal Probability plot – Tensile

Through ANOVA the parameters can be categorized into significant and insignificant parameters. The importance of machining parameters was investigated to determine the optimum combinations of the bonding parameters by using ANOVA. F-test provides a decision at some confidence level as to whether these estimates are significantly different.

Table 7. Analysis of Variance - Energy

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	19332.3	6444.1	15.46	0.006
Temperature	1	16537.5	16537.5	39.67	0.001
Pressure	1	2090.7	2090.7	5.01	0.075
Time	1	704.2	704.2	1.69	0.250
Error	5	2084.6	416.9		
Total	8	21416.9			

Table 8. Analysis of Variance – Tensile strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	19332.3	6444.1	15.46	0.006
Temperature	1	16537.5	16537.5	39.67	0.001
Pressure	1	2090.7	2090.7	5.01	0.075
Time	1	704.2	704.2	1.69	0.250
Error	5	2084.6	416.9		
Total	8	21416.9			

From F-value table and ANOVA table 7 & 8, it is found that bonding time is most significant factor and contribution more on both the responses of energy consumption and tensile strength of the diffusion bonded joints.

5. Conclusions

In this paper, effect of diffusion bonding parameters on energy consumption and tensile strength of the joints of Ti-6Al-4V and SS304 stainless Steel was investigated. Experimentation was done as per Taguchi's L9 orthogonal array. Optimal combination of bonding parameters and their levels for minimum energy consumption and maximum tensile strength was obtained and significance of the bonding parameters was determined using ANOVA. Based on the results of the present study following conclusions are drawn: 1). Taguchi's robust design was successfully used for optimizing diffusion bonding parameters 2). Optimal combination of the bonding parameters is found to maximize the tensile strength of the joints as well as to minimize the energy consumption. 3). Holding time contributes maximum followed by bonding temperature and bonding pressure to minimize the energy consumption. Tensile strength of the joints is mostly contributed by holding time followed by bonding pressure and bonding temperature.

6. References

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