International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Estimation of Fatigue life of Ti-6Al-4V welded joints using Response Surface Methodology and simulation through Abaqus

Srinivasareddy Vempati[#]*, K.Brahma Raju^ and K.Venkata Subbaiah[!]

[#]Department of Mechanical Engineering, QIS College of Engineering & Technology, Ongole , Andhra Pradesh, India
^Department of Mechanical Engineering, SRKR Engineering College, Bhimavaram, Andhra Pradesh, India
[!]Department of Mechanical Engineering, A.U College of Engineering (A), Andhra University Visakhapatnam, Andhra Pradesh, India

Received 12 Oct 2018, Accepted 15 Dec 2018, Available online 17 Dec, **Vol.8, No.6 (Nov/Dec 2018)**

Abstract

Weld joints of Titanium alloys are used widely in fatigue loaded applications. The failures of welded joints are in the appearance of crack propagation due to fatigue load. The Main objective of present work is to identify the fatigue strength, fatigue life of welded joints of Ti alloy (grade 5) .The welded plates are joined in the cruciform shape using Tungsten Inert Gas weld and ERTi-5 as filler material. The specimens are tested on Instron servo hydraulic fatigue testing machine under constant load ratio(R=0) and frequency of 10Hz. Fatigue life of welded joints is influenced by the geometrical parameters like weld size, weld shape, plate thickness, weld penetration and fillet angle. Using RSM and ANOVA optimum values of geometrical parameters and their significance can be determined to obtain better fatigue life and fatigue strength and Simulation is to done to predict the failure of joints for different weld shape.

Keywords: *Response surface Methodology, fatigue life, Design Matrix, Anova technique*

1. Introduction

The increase in use of titanium alloy in various applications such as Aerospace, naval, chemical and biomedical engineering (C.Casavola, 2009).The tensile strength of titanium alloy can read 1050Mpa based on heat treatment and chemical composition present today, It became necessary to investigate the applications of titanium alloy welded joint subjected to fatigue load.This Research aims to identify the geometrical parameters of cruciform welded joint of grade 5 of various weld shapes under fatigue loads. Experimental tests are conducted in order to find out the optimum geometrical parameters with help of Response surface methodology to obtain the optimum response which is known as fatigue life.

In this paper the role of Fractographs on Mechanical and fatigue properties of Ti 6al 4v grade 5 welded plates were studies by analyzing the microstructure of welded plate and fatigue loaded welded plates are visualized with help of scanning electron microscope.

In this investigation an attempt has been made to develop mathematical models to predict fatigue properties of pulsed current TIG welded titanium grade 5 weld joints. By means of the mathematical models, the geometrical parameters and strength of the weld joints can be predicted with 90% confidence level. M.Balasubramanian et al made an attempt to develop mathematical models to forecast tensile properties of GTA welded titanium alloy weldments by using RSM and ANOVA Technique Ramanjaneyulu.K et al developed Regression equations based on the experimental values of maximum tensile strength and percentage elongation of the friction stir welded joints of aluminum alloy. He observed that developed models can be use to expect the responses within ±10% of their experimental values at 95% confidence level.

Olabi *et al* studied RSM to examine the effect of laser welding parameters on residual stress distribution at various locations from the weld centre line of AISI304 butt joints

Kundan *et al* studied that TIG welding is one of the best material joining processes extensively used in industry. In his investigation he had made an attempt to develop the relationship to forecast the fatigue life by means of statistical tools such as DoE, ANOVA and regression analysis using Mini Tab Software 17.

In cruciform joints, usually identified defect is LOP, which is occurred at the joint because lack of access to the root region during process of fabrication. The structures of this welded joints present are frequently subjected to a fatigue type of loading. This might result in the beginning of a fatigue crack at the LOP defect,

*Corresponding author's ORCID ID: 0000-0001-9427-2098
DOI: https://doi.org/10.14741/ijcet/v.8.6.18

and the propagating of these cracks in the weld metal will result in the failure of the joint (B. Ravindra, 2011). The LOP defect will influence the fatigue behavior of a fillet weld when its size increases; fatigue life is reduced significantly, this happens when the size of LOP is equal to half of the plate thickness. The failure of joint cannot be prevented apart from the required weld sizes by analyzing appropriately (G. Casalino, 2005).

2. Experiment procedure

Fig 1. Fabrication of specimens

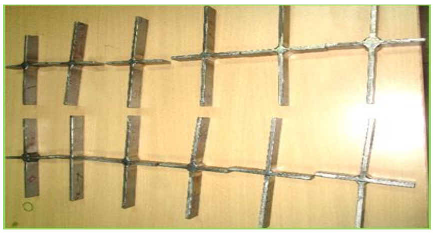

Fig 2. Fabricated Specimens for fatigue testing

In present work Ti-6Al 4V plate (Grade 5) used as specimen and its chemical & mechanical properties are shown in Table 1 &2. The dimension of the main plate and two cross plates are 100 mm long × 24 mm width and thickness of 6 mm. Tungsten inert gas arc welding is done to join the plates in cruciform shape by using ER Ti5 filler rod material with help of TIG welding machine. Titanium gr-5 plates are rarely available

Table 1. Geometrical parameters and its levels

Control Parameters	Symbol	Levels	
		Low(-1)	High(+1)
Initial LOP/filler width (a/w)	C	0.2	0.6
Leg length/plate thickness(L/Tp)	P	0.6	1
Fillet angle	f	30 degrees	60 degrees
Nominal stress	S	152Mpa	670 Mpa

In design matrix the geometric control parameters and its levels are given in table 1

2.1 Fatigue Test

Cruciform shape welded are placed in the grippers and experiments were conducted with constant ratio (R=0) and exciting load is applied on the cross plate of specimen with frequency of 10Hz. By applying the stress range on specimen and to attain failure of joint at welded part was recorded in the form of number of cycles which is observed in table 5 as a output response.

Fig 3. Specimen placed in Fatigue testing Machine

Xi in the equation is the resulting coded value of a variable X, here X indicates a value of the variable between X max to X min, and X min is the inferior and X max is the greater limit of the variable. The control parameters with levels are shown in Table 2. Total of 16 experiments, 2 levels with four factors were performed, to obtain output response as fatigue life.

The sixteen experiments has been formulate in the form of as per 2^4factorial design (two levels and four factors) and in support of major effects with the formula 2^{nc-1} for the low (-1) and high (+1) values. Wheren_c refers to Number of columns.

By applying different stress ranges on the material the number of cycles are recorded.16 Experimental tests were done to arrive the design matrix.

2.2 Design of Experiments and Response Surface Methodology

By observing above conditions, the levels of the parameters are chosen in such a manner that the grade 5 alloy is to be welded with no any weld defects. For the ease of recording and giving out the experimental data, the superior and inferior levels of the control factors are has been indicated as +1 and -1 and these coded values of every intermediate levels can be calculate by using the expression Xi. RSM is a set of exact and geometric techniques helpful for analyzing the problems in which numerous nondependent variables which the influence a response. Main aim of the RSM is to find those settings of process parameters that give most favorable value of the response. RSM provides a regression form that establishes relationship among the control parameters and response. This relationship can be used to predict the response when the process parameters are varied within the chosen ranges.

Table 2. Experimental layout using CCD with Fatigue life data

Expt No	Specimen ID	Geometrical Parameters				Fatigue life is $Nx10^5$
		Initial LOP/ fillet width (C)	Leg length/plate thickness (P)	Fillet angle (f)	Nominal stress (S)	
1	C1	-1	-1	-1	-1	3.16
2	C2	1	-1	-1	-1	1.65
3	C3	-1	1	-1	-1	2.25
4	C4	1	1	-1	-1	4.19
5	C5	-1	-1	1	-1	3.27
6	C6	1	-1	1	-1	2.89
7	C7	-1	1	1	-1	4.68
8	C8	1	1	1	-1	2.43
9	C9	-1	-1	-1	1	0.21
10	C10	1	-1	-1	1	0.68
11	C11	-1	1	-1	1	2.16
12	C12	1	1	-1	1	0.90
13	C13	-1	-1	1	1	0.22
14	C14	1	-1	1	1	0.34
15	C15	-1	1	1	1	0.62
16	C16	1	1	1	1	0.75

Table 3. ANOVA for Fatigue Life using Adj Sum of squares for Test

Source	Dof	Seq SS	Adj SS	Adj MS	F	P	
C	1	2.295	2.295	2.295	4.13	0.057	significant
P	1	4.928	4.928	4.928	8.86	0.013	significant
f	1	0.6889	0.688	0.688	1.24	0.289	
S	1	30.1401	30.140	30.14	54.2	0.367	
C*P	1	0.205	0.205	0.205	2.46	0.025	significant
C*S	1	0.070	0.070	0.070	0.84	0.75	
P*f	1	0.890	0.890	0.890	10.68	0.043	significant
P*S	1	1.257	1.257	1.257	15.84	1.05	
f*S	1	0.369	0.369	0.369	4.428	0.13	
Error	11	6.1169	6.1169	0.556			
Total	15	44.1695					
S= 0.745707 R-Sq = 86.15% R-Sq(adj) = 87.12%							
PRESS = 12.9415 R-Sq(pred) = 85.70%							

Fatigue life is function of four factors thus the linear polynomial regression equation can be expressed as

$Y = \alpha_0 + \Sigma\alpha_i x_i + \Sigma\alpha_{ij} x_i x_j + \varepsilon_0$

$Y = \alpha_0+\alpha_1x_1+\alpha_2x_2+\alpha_3x_3+\alpha_4x_4+\alpha_{12}x_1x_2+\alpha_{13}x_1x_3+\alpha_{14}x_1x_4+\alpha_{23}x_2x_3+\alpha_{24}x_2x_4+\alpha_3x_3x_4$

3. Mathematical Modelling

CCD's are well known as response surface designs which can fit a complete quadratic form. For our convenience, assume each factor varies from -1 to +1.

To find out the approximate regression coefficients, few number of investigational design methods are presented. In present work, CCD is used which fits in the second order response surface precisely. Coefficients of all parameters a will be obtained by applying CCD by using the Mini tab software. By determining the major coefficient, the final correlation was developed by means of only these coefficients.

The relationship to expect the fatigue life of TIG weld joints of grade 5 is specified by following equation

Fatigue life = (2.1075–0.3788 C+0.5550 P-0.2075 f – 1.3725-0.2163 CP+0.0812 CP +0.3113 CS- 0.3350 Pf - 0.1825 PS -0.0450f S) x 10^5.....(3)

The coefficient of (R^2) is used to come across the closeness of experimental and predicted values which is calculated by means of the following expression

$R^2 = \Sigma\,(Y_P - Y_a)^2 / \Sigma(Y_e - Y_a)^2$

PredR^2 of 0.8615 is in sensible conformity by means of the AdjR^2 of 0.8712. Adeq Precision will trial the S/N ratio. Above consideration indicates a sufficiency of the developed empirical relationship.

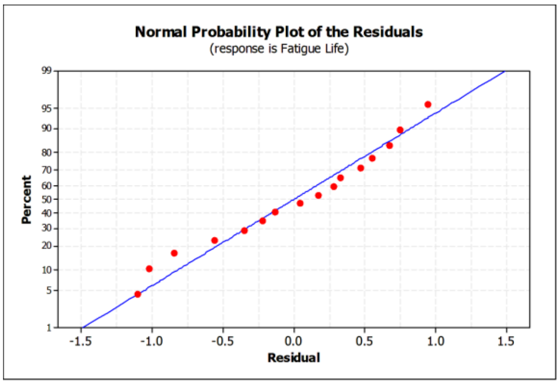

Fig 5. Normal probability plot of the Residuals

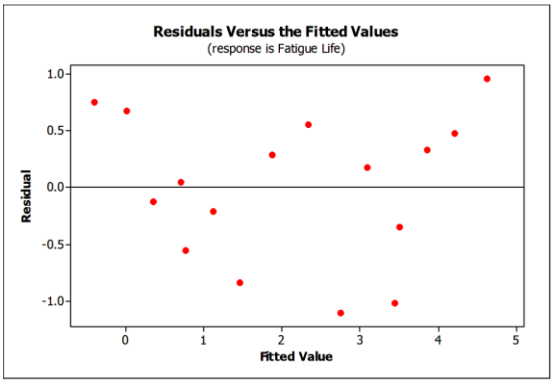

Fig 6.Residual vs Fitted Value

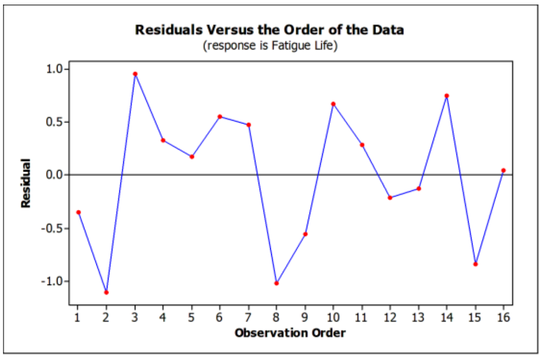

Fig 7.Residuals vs Observation order

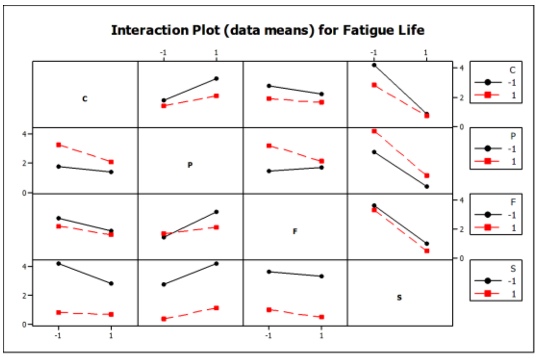

Fig 8.Interaction Plot

Fig.5 shows that residuals are located along the reference straight line, which shows the errors were scattered normally. This consideration indicates the sufficient value of the regression model.

From Fig 6 it is identified that the steady variance assumption was verified with plot of residuals vs fits. This plot represents to show a random pattern of residuals on either sides of 0 and it does not disclose any familiar patterns. Therefore common pattern is considered that the when residuals values increase as the fitted values increase the fatigue life.

The observations should be randomly selected from the centre line and therefore assumption is violated therefore independent assumption is to be satisfied if the plot does not make known of any pattern as shown in Fig 7.

The fatigue strength for each experimental run is investigated by using the interaction plot is shown in Fig 8. The interaction plot illustrates an interaction between all the levels and parameters for effective optimization From figure, it shows that the lines are not parallel to each other for all levels of factors.

It is considered that to obtain optimum fatigue strength the geometrical parameters for the Ti 6al 4v joint are as follows a/W = 0.2 ,L/Tp =1 , f= 30^0-45^0 and S= 220 Mpa. For above control parameters the experimental result for fatigue strength is $2.25x10^5$

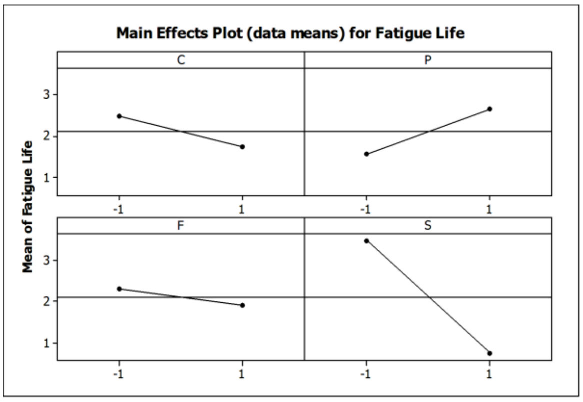

Fig 9. Main effect plot for Fatigue life

The optimum values of geometrical parameters are C= -1(low) P= +1(high) f = -1(low) S = -1(high)Lower a/W ratio, Higher L/T_p ratio, less fillet angle and lower nominal stress value gives the optimum value for fatigue life is around $1.7x10^5$ cycle as Shown in Fig 9.

4. Simulation of Welded joints

The load was applied as pressure on the web plate along Z direction. The applied pressure intensity in terms of stress ranges were decided as the percentage of the yield strength (306MPa) of the material. The flange plate was fixed by boundary condition. Figure 8 shows the loading and boundary conditions.

The mesh was generated with hexahedron elements and sweep meshing technique. The element type was given as quadratic for plates and linear for welded portion. C3D8R (Continuum three dimensional 8 noded quadratic brick reduced integration) were used. Figure 9 shows the mesh modeling on fillet welded joints.

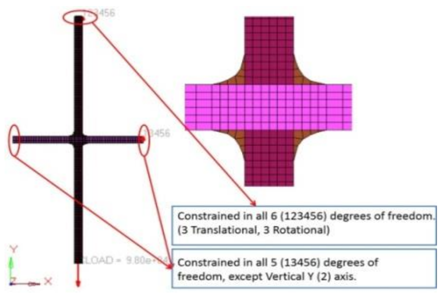

Fig 10. Boundary Condition for cruciform welded joints

Element type: Full-integration, 3D elements (type C3D8) should be used for all crack growth calculations. If the geometry is inherently 2D, then it should be modeled as a thin, 3D plate with suitable boundary conditions to represent the plane strain or plane stress conditions.

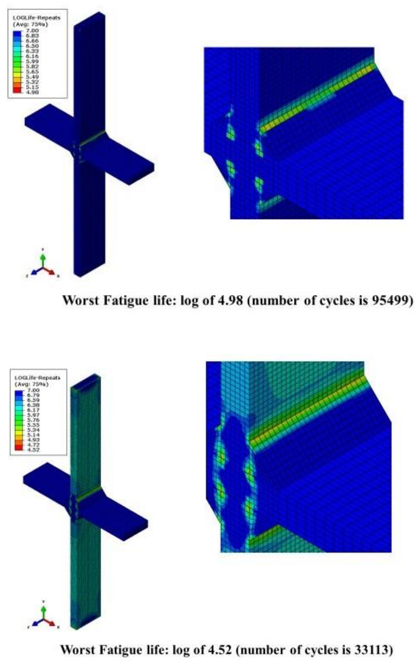

Fig 11. Fatigue analysis of Cruciform shape weld joints using Abaqus software

Table 4 .Fatigue life comparison between RSM and Abaqus

S.No	Fatigue Life		
Applied stress	RSM	Abaqus	
150 MPa	$1.65 X10^{5}$	95499 cycles	$0.95 X10^{5}$
670 MPa	$0.34 x10^{5}$	33113 cycles	$0.33 x10^{5}$

Conclusions

The geometrical parameters and the only some Interactions are found to be significant in determining the weld strength of the cruciform welded specimens. Empirical relationship is arrived to forecast the Number of cycles of load carrying TIG weld joints of Ti 6Al 4V grade 5

a) The developed relationship is successfully used to find out the fatigue life and geometrical properties of load carrying TIG welded cruciform joints failing from weld area at 87 % confidence level

b) The studies on cruciform welded joint proportions on fatigue life were analyzed in detail. Lower a/W ratio, Larger weld size(L/Tp ratio), moderate fillet angle and nominal stress value gives better fatigue life when compared with other combinations.

c) Fatigue Life obtained through RSM technique and Simulation is compared and found that there is only 10 % variation and validates the present work.

References

C.Casavola, C.Pappalettere, F.Tattoli Experimental and numerical study of static and fatigue properties of titanium alloy welded joints.*Mechanics of materials*,March 2009,Vol.41(3):231-243

M. Balasubramanian, V. JayabalanDeveloping mathematical models to predict tensile properties of pulsed current gas tungsten arc welded Ti–6Al–4V alloy.*Materials and Design* 29 (2008) pp. 92–97

RamanjaneyuluK ,Madhusudhan Reddy G , Hina G Optimization of process parameters of aluminum alloy AA 2014-T6 friction stir welds by response surface methodology.*Defence Technology 11* (2015) 209- 219

A. G. Olabi, G. Casalino, K. Y. Benyounis and M. S. J. Hashmi, An ANN and Taguchi Algorithms Integrated Approach to the Optimization of CO2 Laser Welding.

Kundan K, Somnath C, Avadhesh Y, 2012, Surface response methodology for predicting the output responses of TIG welding process.*Asian Journal of Engineering Research* ISSN--2319–2100, Asian J Eng Res/Vol. I/Issue

B. Ravindra, T. Senthil Kumar, V. Balasubramanian. Fatigue life prediction of gas metal arc welded cruciform joints of AA7075 aluminum alloy failing from root region. *Transactions of Non Ferrous metals society of china* 21 (2011)-1210-1217

HobbacherA. Recommendations for fatigue design of welded joints and components IIW Doc, No. XIII-1939-96/XV-845-96. 1996.

Maddox S J. Recent advances in the fatigue assessment of weld imperfections. Welding J, 1993, 72: 42-52

G. Casalino, F. Curcio and F. M. C. Minutolo, Investigation on Ti6Al4V Laser Welding Using Statistical and Taguchi Approaches, *Journal of Materials ProcessingTechnology*, Vol. 167, No. 2-3, 2005, pp. 422-428.

AI. Khuri and J. A. Cornell, Response Surfaces Design and Analysis, 2nd Edition, Marcel Dekker, New York, 1996.

Gunaraj V, Murugan N. Application of response surface methodology for predicting weld bead quality in submerged arc welding of pipes.*J Mater Process Technol*, 1999, 88: 266-275. Usami S, Kusumoto S.Fatigue strength of cruciform, tee and lap joints. Trans Jpn Welding Soc, 1978,9:1-10

D. C. Montgomery, Design and Analysis of Experiments, 2nd Edition, Wiley, New York, 2007.

T. S. Balasubramanian M. A. Muthu Manickam Effect of welding processes on joint characteristics of Ti–6Al–4V alloyMinerals and Mining Published by Maney on behalf of the Institute

Elangovan K, Balasubramanian V, Babu S. Predicting tensile strength of friction stir welded AA 6061 aluminum alloy joints by mathematical model. *Material Design*2009;30:188-93

Mori, T. and Kainuma, S. (2001) A Study on Fatigue Strength Evaluation Method for Load-Carrying Fillet Welded Cruciform Joints *International Institute of Welding, XIII-1884-01.*

Frank, K.H. and Fisher, J.W. (1979). Fatigue Strength of Fillet Welded Cruciform Joints. Proceedings of ASCE, ST9, pp.1727-1740.