EFFECT OF FRETTING FATIGUE PARAMETERS ON FIR-TREE JOINT OF AERO-ENGINE BLADE DISC INTERFACE

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Abstract*—*In gas turbine engine, one of the major failure is due to fretting fatigue at turbine blade/disc joints. Fretting fatigue generally leads to the degradation of fatigue strength of material due cyclic micro-slip between contacting surfaces. The present study focuses on achieving optimal blade/disc parametric combination in order to minimize stress distribution and effect of fretting fatigue based on Response Surface Method (RSM). In this work most effective geometrical parameters like bottom flank angle, skew angle and number teeth are considered as variables affecting on stress distribution such as von-mises stress, maximum principle stress, shear stress, and contact pressure. Second-order quadratic models are developed for all responses, using central composite design. The developed models are used to determine the optimum parameters. These optimized geometrical parameters are validated as the response values are in reasonable agreement with the predicted values.

Index Terms*— *Fir-tree assembly, Fretting Fatigue, Finite Element, Central composite design, Optimization

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I. INTRODUCTION

In gas turbine engines one of critical components which can fail due to fretting fatigue is blade/disc attachment at the fir tree joint [1]. Although this joint is nominally fixed, micro-scale relative movement at the interface occurs between contacting bodies experience both centrifugal and oscillatory tangential movement vibrations resulting in damage and causes a significant reduction in fatigue life. Fretting is not caused by the visible corrosion, but by small shear stress initiated by fatigue cracks at the edges of the contact zone [2]. If two blocks are clamped together under a normal force, so that they partially overlap to form a contact zone, and then cyclically loaded placing the contact zone in shear, the maximum shear stress will occur at each end of the contact zone. This edge of contact is the initial location of fretting fatigue. Fatigue failure results from the cracks then propagating under the applied normal stresses on through the component.

Jianfu Hou et al. [3] investigated gas turbine blade for mechanical and fatigue loads to evaluate the steady state stresses and dynamic stresses a non-linear finite element analysis was performed. From the analysis, peak stress was found at the top fir-tree trailing corner. Lucjan Witek et al. [4] the high stress location at the fir-tree root was analyzed with help finite element (FE) method by applying the different rotational and analysis has been carried-out using the ABACUS tool. From the analysis, peak stress was found at the 3rd lower slot corner. It was also observed that, increase of plastic strain at constant rate from 16000 rpm till 20000 rpm. B Kenny et al. [5] at turbine disc and blade joint region the stress distributions were evaluated using the technique called two dimensional photo-elastic frozen for axially loaded assembly. This study showed that below the contact surfaces, the steep gradients of principle stress were found adjacent to fillet radius region. Delhelay [6] adopted a thermo-mechanical analysis in the fir-tree joint. To evaluate stress distribution in 2-D and 3-D geometries by considering non-linear contact conditions. It was observed that the bottom tooth was subjected to the highest stress value. Singh et al. [7] analyzed the fir-tree region of a turbine disc and attached blade by treating the total fir-tree region as an assembly of many steps to obtain its stiffness and deflection using the FE method. It was observed that all the deflections depend on the geometrical parameters of fir-tree region and the variation has been found to be nearly linear.

The present study focuses to assess the effects of fir-tree parameters such as bottom flank angle (30^0, 40^0 and 50^0), skew angle (0^0, 10^0, 20^0) and number of teeth (3, 4, 5) at constant co-efficient of friction (0.3) on stress and pressure distribution at the fir-tree region of aero-engine turbine blade disc joint using FE analysis and to carry out the analysis of variance of parameters and responses using MINITAB 17.0 to identify the significant effects of these parameters on computed responses.

II. DESIGN OF EXPERIMENTS

Statistical design of experiments has several advantages over classical optimization methods, where one parameter is optimized at each time [8]. In order to obtain required data in statistical design all experiments/analysis are carried out in planed way and result can be analyzed systematically. Response surface method (RSM) is a sum of statistical and mathematical method enabling more data collection with lower number of experiments [9-10]. In RSM, every parameters should have at least three levels so that parabolic effects can be determined. Central composite design (CCD) one of the commonly used RSM technique in CCD design, all process variables are studied in three levels (-1, 0, and +1) each of these values is a code for an original variable value. Coding the variable levels is a simple linear transformation of the original measurement scale so that the highest value of the original variable becomes (+1) and the lowest value becomes (-1). The average of these two values is assigned to (0) the α values depends on the number of variables studied (3 in our case) and for two, three, and four variables, they are 1.41, 1.68, and 2.00, respectively [11-13].

In this study central composite design (CCD) with three levels and three factors is applied to investigate the influence of process parameters (Bottom flank angle, Skew angle, and Number of teeth) on multiple responses including: equivalent von-Mises stress, maximum principle stress, minimum principle stress, maximum shear stress and contact pressure. Parameters and there levels considered for present study are shown in Table 1. Design matrix for a rotatable CCD for above parameters obtained using MINITAB which gave 20 design points.

Table 1: Parameters and their levels

Parameters	Coded values		
	-1	0	1
	Original values		
Bottom flank angle	30^0	40^0	50^0
Skew angle	0^0	10^0	20^0
Number of teeth	3	4	5

III. NONLINEAR STRUCTURAL ANALYSIS

Based on CCD design matrix geometrical models for fir-tree region of aero-engine turbine disc and attached blade were modeled in UNIGRAPHICS with appropriate dimensions. The basic dimensions for the model based on [14-15], 3-D fir-tree model for combination of (bottom flank angle (40^0), skew angle (0^0), and number of teeth (4)) which has been modeled using UNIGRAPHICS is as shown in Figure 1. Parasolid file of the model was then imported into FE analysis package ANSYS 17.0., nickel base super alloy commonly known as INCONEL-718 is used for disc and blades [16-18]. The properties of material used for analysis were young modulus E=2.1E+05 MPa, poisons ration μ= 0.3, Density (ρ) = 8220 kg/m3 the disc is considered as target (TARGE 170) and blade considered as contact (CONTA 174). All the models examined were subjected to centrifugal load only with angular velocity of 10000rpm. Due to presence of non-conservation frictional forces, the loading was applied incrementally and load step in each increment was automatically calculated within the FE code. Twenty analysis run were performed to measure the responses. Figure 2 shows the equivalent stress plot obtained from the ANSYS 17.0. for combination of (bottom flank angle (40^0), skew angle (0^0), number of teeth(4)) and Table 2 shows combination of experiments based on CCD and corresponding measured response.

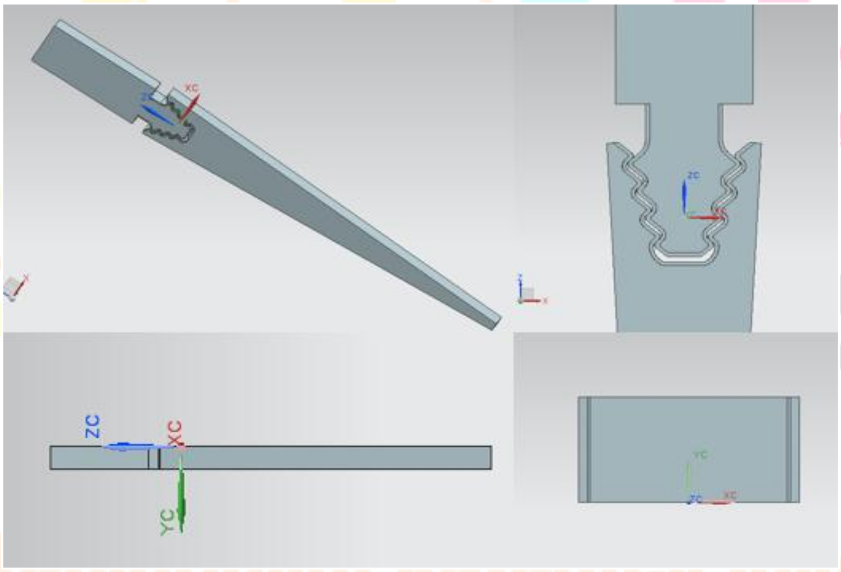

Figure 1: 3-D model of fir-tree joint

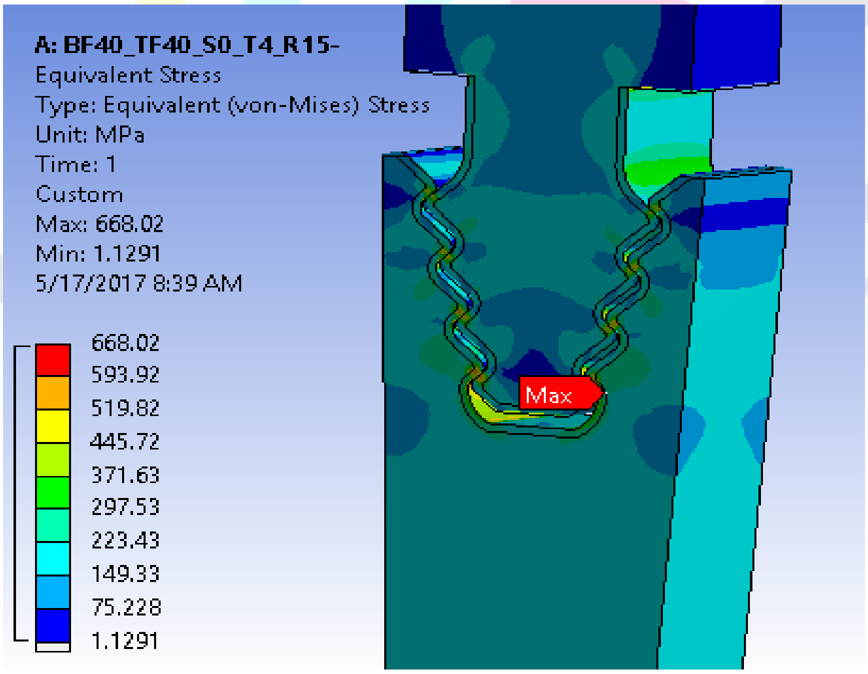

Figure 2: Equivalent stress plot

Table 2: Combination of experiments based on CCD and corresponding measured response

Run	Actual values of parameters			Measured response values				
	A	B	C	Eq. Stress (Mpa)	Max. P.Stress (Mpa)	Min. P.Stress (Mpa)	Shear Stress (Mpa)	Contact Pressure (Mpa)
1	50	0	3	643.04	756.53	755.71	342.37	766.74
2	30	0	3	717.67	865.12	1015.3	416.69	1011.6
3	40	10	5	746.16	818.68	739.2	328.04	753.18
4	40	10	4	803.38	880.51	852.36	371.85	787.54
5	40	10	4	803.38	880.51	852.36	371.85	787.54
6	50	0	5	631.21	707.33	640.19	230.55	668.2
7	40	20	4	936.74	989.07	1071.9	415.79	974.89
8	50	20	3	976.26	1018.4	1162.2	366.02	1254.4
9	30	20	5	832.73	926.47	1074.2	379.59	1072.3
10	40	10	4	803.38	880.51	852.36	371.85	787.54
11	40	10	4	803.38	880.51	852.36	371.85	787.54
12	40	10	4	803.38	880.51	852.36	371.85	787.54
13	40	10	4	803.38	880.51	852.36	371.85	787.54
14	30	0	5	648.95	774.34	312.08	296.56	789.57
15	40	0	4	668.02	764.62	674.31	294.66	632.4
16	40	10	3	928.16	921.53	1021.7	421.54	938.57
17	30	10	4	745.64	872.45	1091	372.96	1061.9
18	50	10	4	742.86	833.14	841.67	315.16	909.22
19	30	20	3	940.97	1056.2	511.33	1335.4	1308.3
20	50	20	5	833.16	853.77	876.72	304.27	1030.8

IV. RESULT AND DISCUSSION

Development of regression model equations using CCD

The computed values of responses were fed into MINITAB 17.0 to analyze the effect of fretting fatigue parameters on the computed responses. Using MINITAB 17.0 regression models for each of the responses were developed using RSM to compare and correlate the response. Regression equation for responses such von-misses stress maximum principle stress, minimum principle stress, shear stress, and contact pressure is given by equation 1-5 respectively where bottom flank angle (A), Skew angle (B), Number of teeth(C).

Von-Mises stress $= 539 + 43.7*A + 14.37*B - 314*C - 0.588*A*A - 0.006*B*B$
$+34.1*C*C + 0.1601*A*B + 0.275*A*C - 2.135*B*C$
R-sq. $= 97.21\%$ (1)

Maximum principle Stress $= 851 + 8.74*A + 12.70*B - 44.8*C - 0.1643*A*A - 0.0762*$
$B*B + 0.88*C*C + .0814*A*B + .084*A*C - 1.930*B*C$
R-sq. $= 98.50\%$ (2)

Minimum principle Stress $= 828 + 15.7*A + 49.1*B - 331*C - .33*A*A - 0.60*B*B$
$+53*C*C + .481*A*B + 3.26*A*C - 13.70*B*C$
$*C*C + .481*A*B + 3.26*A*C - 13.70*B*C$
R-sq. $= 65.50\%$ (3)

Maximum shear Stress $= 3354 - 61.4*A + 90.7*B - 885*C + .190*A*A + .301*B*$
$B + 49.7*C*C - 1.130*A*B + 11.28*A*C - 9.82*B*C$
R-sq. $= 83.65$ (4)

Contact pressure $= 4841 - 153.7*A + 13.17*B - 404*C + 1.717*A*A - .102*B$
$*B + 32.1*C*C - .3385*A*B + 1.699*A*C - 1.738*B*C$
R-sq. $= 99.29\%$ (5)

In above all equation value of R-sq., represents confidence level of regression. It's found that all the responses are within desirable range [19] except for minimum principle stress. This is because considered variables (bottom flank angle, skew angle, number of teeth) have less influence on minimum principle stress.

Statistical analysis of response

The adequacy of the models was further justified through analysis of variance using analysis of response design. Result of ANOVA for all 5 responses are listed in Table 3 The table summarizes Fcal and P-value where *P*-Value is the probability value used to determine the effect in the model that was statistically significant [20]., the smaller the *P*-value, the more significant was the corresponding coefficient [21]. On the basis of P values as observed form table it's found that von-mises stress is influenced by skew angle, number of teeth, bottom flank angle vs bottom flank, number of teeth vs number teeth and skew angle vs number of teeth. Maximum principle stress is influenced by bottom flank angle, skew angle, number of teeth, and skew angle vs number of teeth. Maximum shear stress is influenced by bottom flank angle, skew angle, number of teeth and its interaction like bottom flank angle vs number of teeth and bottom flank angle vs skew angle, Contact pressure is influenced by bottom flank angle, skew angle, number of teeth and it's interaction except skew vs skew angle.

Table 3: Analysis of variance (ANOVA) of response surface for all five response.

Parameters	Eq. Stress		Max. P. Stress		Min. P. stress		Shear stress		Contact Stress	
	Fcal	P	Fcal	P	Fcal	P	Fcal	P	Fcal	P
A	0.65	0.44	50.07	0	0.21	0.658	986	0.01	8380	0
B	268.24	0	450.4	0	4.72	0.055	9.51	0.01	697.4	0
C	48.31	0	136.5	0	1.9	0.198	11.52	0.01	207	0
A*A	17.38	0.002	3.51	0.091	0.09	0.776	0.06	0.81	108.1	0
B*B	0	0.96	0.76	0.405	0.28	0.611	0.16	0.7	0.63	0.445
C*C	5.86	0.036	0.01	0.922	0.21	0.655	0.43	0.53	6.28	0.031
A*B	3.75	0.082	2.5	0.145	0.52	0.488	6.53	0.03	20.36	0.001
A*C	0.11	0.746	0.03	0.874	0.24	0.636	6.5	0.03	5.13	0.047
B*C	6.67	0.027	14.09	0.004	4.2	0.068	4.93	0.05	5.37	0.043

Effect of model parameters on responses Equations

The Effect of model parameters on responses in the three-dimensional (3D) surface plots obtained using multi objective response optimizer. Figure 3 (a)-(b) shows 3D surface plots for each responses versus two varying parameters i.e. bottom flank angle and skew angle at a fixed value of the third operating parameter i.e. number of teeth. From figures it's observed that as bottom flank angle increase from 30^0 to 50^0 and skew angle decreases from 20^0 to 0^0 all measuring responses decreases gradually except contact pressure where min responses is observed in range of 40^0 to 50^0.

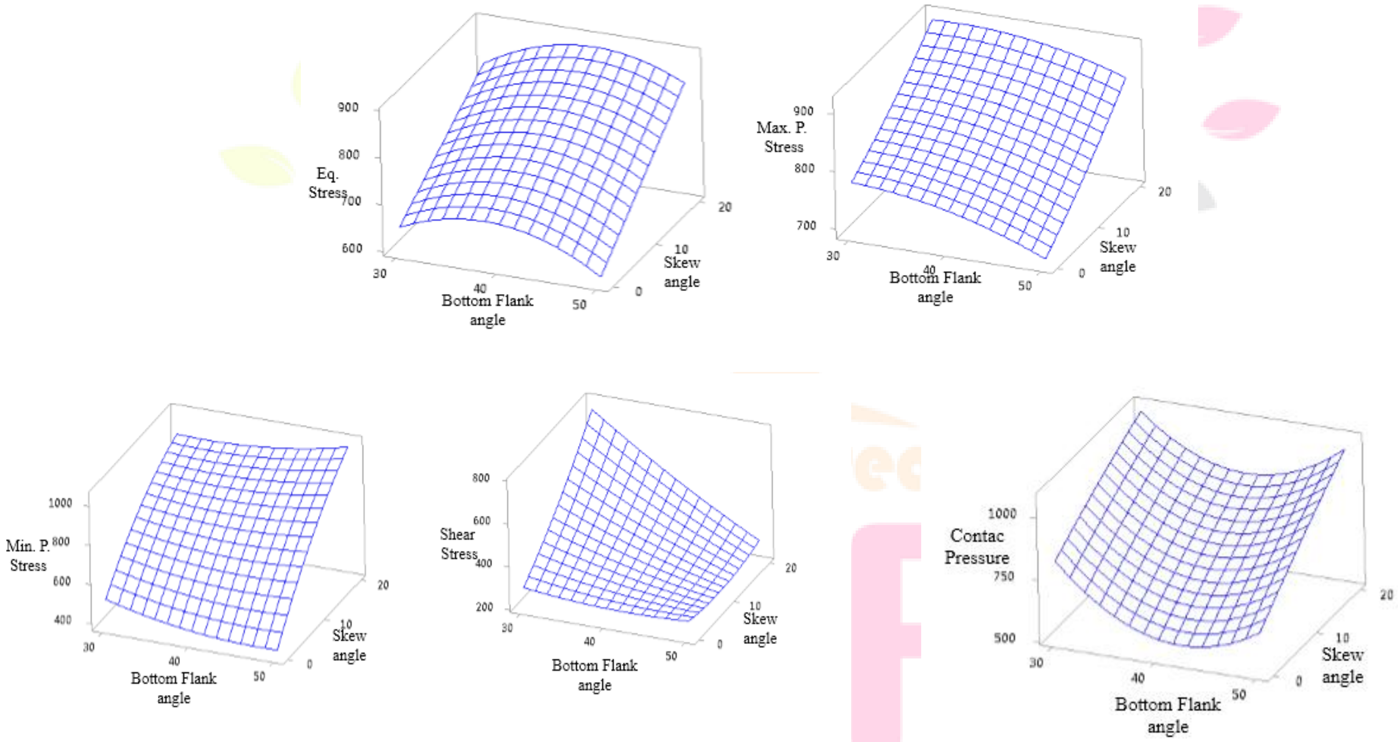

Figure 3: Response surface plots for (a) Von-mises as function bottom flank angle and Skew angle (b) Maximum principle stress as function bottom flank angle and Skew angle (c) Minimum principle stress as function bottom flank angle and Skew angle (d) Shear stress as function bottom flank angle and Skew angle (e) Contact stress as function bottom flank angle and Skew angle.

Optimized condition for minimum response

The final step in any CCD is to predict the response at the optimal conditions. Then, confirmation experiments are done to verify the prediction. Using the obtained CCD models, optimum parameter values for the defined goals (in this case, the goal is to set target value for minimum response) determined using response optimizer [22]. In this project work the target value was taken as the minimum value of the response. For several responses, all goals are combined into an overall desirability function that has to be minimized. Several solutions will be obtained with a minimized desirability function (values near to one) that could be arbitrarily selected based on the process requirements. In this study, numerical optimization was carried out for minimum responses using MINITAB-17, and the desirability functions were considered for the optimization. The main purpose of this study was to find the optimum conditions for minimum response. To achieve this goal, firstly, the numerical optimization technique was applied to optimize all five responses simultaneously and then, each response was optimized individually. For multi-response optimization, the optimum condition was Bottom flank angle (48.59^0), Skew angle (0^0) and Number of teeth (5). At this condition respective analysis values for equivalent von mises stress, Maximum principle stress, Minimum principle stress, Shear stress and Contact pressure were 665 Mpa, 732.05 Mpa, 419.53 Mpa, 374.7 Mpa, and 668.32 Mpa which are in close agreement with the predicted values of, 625.77Mpa, 706.163 Mpa, 401.6391 Mpa, 376.0101 Mpa, and 622.9197 Mpa. The individually optimized values of bottom flank angle, skew angle and number of teeth were: 48.1227^0, 0^0 and 5, respectively for von mises stress, 48.4141^0, 0^0 and 5, respectively for Maximum principle stress, 47.9798^0, 0^0 and 5 respectively for Minimum principle stress, 31.1010^0, 1^0 and 5 respectively for shear stress and 35.4545^0, 0, and 5 respectively for contact pressure.

V. CONCLUSION

FE analysis on effect of fretting fatigue parameters on fir tree joint was carried out by using ANSYS 17.0 and the response were analyzed using statistical analysis tool MINITAB 17.0., the following conclusions are presented from this study.

- Analysis of variances (ANOVA) reveals that all the responses were influenced by bottom flank angle, skew angle and number of teeth. From 3D surface plots it has been observed that as bottom flank angle increases and skew angle decreases, all response values decreases gradually.
- Optimization of parameters were carried out, it is found that bottom flank angle (48.59^0), Skew angle (0^0) and number of teeth (5). Under this optimum point von mises stress 625.77 Mpa, maximum principle stress 706.163 Mpa, minimum principle stress 401.6391 Mpa, shear stress 376.0101 Mpa and contact pressure 622.9197 Mpa were obtained.

REFERENCES

[1] Papanikos P., Meguid S. A. and Stjepanovic Z, “Three dimensional nonlinear finite element analysis of dovetail joints in aero-engine discs”, Finite Element in Analysis and Design, Vol. 29, 1998, pp. 173-186.

[2] LoveleenKumar. Bhagi., Prof. Pardeep Gupta, “A Brief Review on Failure of Turbine Blades”, Smart Technologies for Mechanical Engineering, Vol. 5, 2013, pp. 25-26

[3] Jianfu Hou, Bryon J. Wicks, Ross A, “Antoniou, An investigation of fatigue failures of turbine blades in a gas turbine engine by mechanical analysis”. Engineering Failure Analysis, Vol. 9, 2002, pp. 201–211

[4] Lucjan Witek, “Failure analysis of turbine disc of an aero engine”, Engineering Failure Analysis, Vol. 13, 2006, pp. 9–17

[5] B Kenny, E A Patterson, M Said and K S S Aradhya, “Contact stress distributions in a turbine disc dovetail type joint-a comparison of photoelasticand finite element results”, Vol. 5, 1991, pp. 21-24

[6] A. J. Durelli, J. W. Dally, W. F. Riley, “Stress and strength studies on turbine blade attachments”, S. E. S. A. Proceedings, Vol. 16, 1957, pp. 171-18

[7] Singh G. D. and Rawtani S, “Fir tree fastenings of turbomachines, blades - I: Deflection analysis”, International Journal of Mechanical Science, Vol. 24, 1982, pp. 377 – 384

[8] Montgomery DC, “Design and analysis of experiments”, Singapore: John Wiley & Sons; 1991.

[9] Parisa Izadiyan, Bahram Hemmateenejad, “Multi-response optimization of factors affecting ultrasonic assisted extraction from Iranian basil using central composite design”, Food chemistry, Vol. 190, 2016, pp. 864-84

[10] Aslan N, “Application of response surface methodology and central composite rotatable design for modeling the influence of some operating variables of a multigravity separator for coal cleaning”, Fuel Vol. 86, 2007, pp. 769–76

[11] Mojtaba Khani, Ali Bahrami, Mohammad D. Ghafari, “Optimization of operating parameters for anti-corrosive biopolymer production by *Chryseobacterium Indologenes MUT.2* using central composite design methodology”, Journal of the Taiwan Institute of Chemical Engineers, Vol.4, 2015, pp. 1–8

[12] Zaharaddeen N. Garba, Idris Bello, Ahmad Galadima d, Aisha Y. Lawal, “Optimization of adsorption conditions using central composite design for the removal of copper (II) and lead (II) by defatted papaya seed”, Karbala International Journal of Modern Science, Vol.2, 2016, pp. 20-28.

[13] DeryaOz Aksoy, Ercan Sagol, “Application of central composite design method to coal flotation: Modelling, optimization and verification”, Fuel, Vol.183, 2016, pp. 609–616

[14] S.A. Meguid, P.S. Kanth and A. Czekanski, “Finite element analysis of fir-tree region in turbine discs”, Finite Elements in Analysis and Design, Vol. 35, 2000, pp. 305-317.

[15] Tiago de Oliveira Vale, Gustavo da Costa Villar, and Joao Carlos Menezes, “Methodology for structural integrity analysis of gas turbine blades”, *J.Aerosp. Technol. Manag., Sao jose dos Campos*, Vol.4, No 1, 2012, pp. 51-59

[16] B. Atxori, G. Meneghetti, L. Susmel, “On The Use Of The Modified Manson-Coffine Curves To Predict Fatigue Lifetime In The Low-Cycle Fatigue Regime”, Journal of Mechanical Engineering, vol. 56, 2010, pp. 27-35

[17] Z. Mazur, A. Luna-Ramırez, J.A. Juarez-Islas, A. Campos-Amezcua, “Failure analysis of a gas turbine blade made of Inconel 738LC alloy”, Engineering Failure Analysis, vol. 12, 2005, pp. 474–486

[18] Shivani Pande, Amit Kumar Pal and Ruby Pant, “Stress analysis and study of fir-tree assembly of turbine disc”, International Journal of Current Engineering and Technology, Vol. 6, 2016, pp. 1252-1256

[19] N. Sahu, J. Acharya, B.C. Meikap, “Optimization of production conditions for activated carbons from tamarind wood by zinc chloride using response surface methodology”, Bioresour.Technol, Vol.101 2010, pp. 1974-1982

[20] Yi X, Shi W, Yu S, Li X, Sun N, He C, “Factorial design applied to flux decline of anionic polyacrylamide removal from water by modified polyvinylidene fluoride ultrafiltration membranes”, Desalination, Vol. 274, 2011, pp.7–12.

[21] Shahabadi SMS, Reyhani A, “Optimization of operating conditions in ultrafiltration process for produced water treatment via the full factorial design methodology”, Sep Purify Tech Vol. 132, 2014, pp. 50–61

[22] Parisa Izadiyan a,c, Bahram Hemmateenejad, “Multi-response optimization of factors affecting ultrasonic assisted extraction from Iranian basil using central composite design”, Food Chemistry, Vol. 190, 2016, pp. 864–870