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Experimental and Theoretical Investigation of Stress Concentration Effect under Thermal and Dynamic Loads on High, Intermediate and Low Pressure Turbine Rotors

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Abstract---Geometric discontinuities cause a large variation of stress and produce a significant increase in stress distribution in the localized area. The high stress due to the variation of geometry is called as 'stress concentration'. This will increase when the loads are further applied. There are many investigators who have studied the stress distribution around the notches, grooves and other irregularities of various machine components. This paper analyses the effects of static, thermal and dynamic loads on a steam turbine rotor of 210MW power station under the operating conditions. An attempt has been made to compare these with experimental results. As experimentation is not possible on real equipment, stress concentration factors for static and dynamic loads are calculated for all three (HPT, IPT and LPT) rotors by strain gauge experimentation method on the prototype models and compared with the results of Finite Element Analysis. After validation, the work is extended on to real geometries. A source code is developed for calculating the nominal stress at each section of rotors. Maximum stress is obtained using FEA at the corresponding section. Static and dynamic Stress Concentration Factors at each section are calculated.

Key words: Stress Concentration Factors, Strain gauge Experimentation, HPT, IPT and LPT Rotors, Static, Thermal and dynamic loads.

1. INTRODUCTION

Peterson R.E. [1] has done significant research on stress concentration of various machine components. Neuber [2] had done exhaustive research on stress concentration factors for extreme thin components. Heteny I. and Lin[3] developed charts for stress concentration factors for notches with flat bottoms. Stress Concentration Factors K_t for opposite U-shaped notches in a finite-width thin beam element are given in the charts by Frocht [4]. And also J.N.Goodier and P.G.Hodge [5] have paid efforts on stress concentration of irregular shapes. For torsion, the membrane analogy was used by Pilkey and Wunderlic [6]. Stress concentration factors for a thin beam element with opposite semicircular notches were found by Isida [7]. The stress concentration factors K_t for flat-bottom notches in a shaft of circular cross-section under tension were given in the charts by Noda [8]. S.J.Hardy and M.K.Pipelzadeh [9] have used the finite element method to obtain stress concentration factor data for flat 'T' shaped components, subjected to axial and shear loading.

The contributions of above in this area are very useful for many investigations. In the literature, it is not available for the cases like determining the stress concentration factors for critical and heavy components such as turbine rotors. Most of the researchers have concentrated or limited their works to only one type of analysis such as either for static or thermal or dynamic.

II. DESCRIPTION

Line diagrams of HPT, IPT and LPT turbine rotors are presented in Fig.1, Fig.2 and Fig.3 respectively. The geometric and elastic properties are as follows.

Rated output	= 210MW
Rated speed	= 3000RPM

In-let steam pressure	= 150Kg/cm^2 (absolute)
In-let steam temperature	= 535^o C
Reheat steam temperature	= 550^o C
Weight of the unit	= 475Tons
Overall length	= 16.97 m
Overall width	= 10.5 m
Rated frequency	= 50 c/s
Maximum permissible speed	= 3090 RPM
Minimum permissible speed	= 2850 RPM
Maximum frequency	= 51.5 c/s
Minimum frequency	= 47.5 c/s

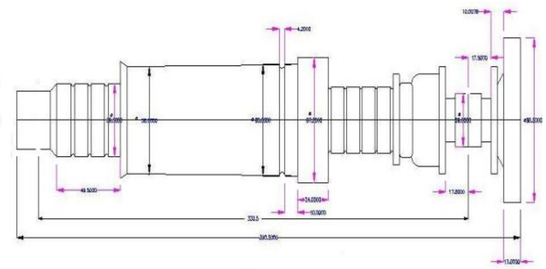

Fig. 1 Line diagram of HPT rotor

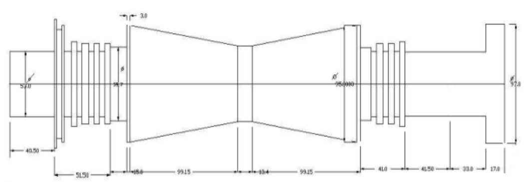

Fig. 2 Line diagram of IPT rotor

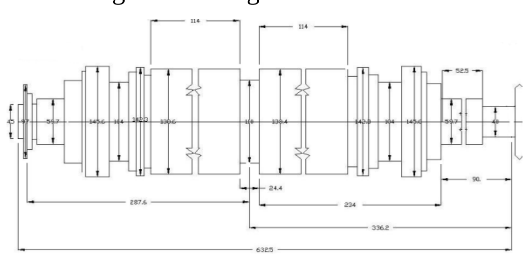

Fig. 3 Line diagram of LPT rotor

III. EXPERIMENTAL INVESTIGATION AND MODELING

The rotors are reduced to prototype models. The dimensions and the loads on HPT, IPT and LPT are scaled down to 20, 30 and 40 times respectively. The magnitude of loads has been also reduced accordingly. The stepped diameters of the rotors are simplified to equivalent diameters without disturbing the blade mounting area. After machining, prototype models are ground and coated. 350Ω resistance foil strain gauges are bonded to models to measure the strains

Strain gauges are available commercially with nominal resistance values from 30 to 3000Ω with 120, 350 and 1000Ω being the most common values. Fig. 4, Fig. 5 and Fig. 6 show the experimental setups for HPT, IPT and LPT respectively. Fig. 7 shows the strain measuring unit.

Fig. 4 Experimental setup of HPT rotor

Fig. 5 Experimental setup of IPT rotor

The micro-strains are obtained at three points on the blade mounting area on prototype model of HPT rotor. The strains are observed as 0.94, 1.20 and 1.24. The recorded strains are then converted into maximum stresses.

Fig. 6 Experimental setup LPT rotor.

Fig. 7 Strain measuring unit

The load versus strain and maximum stress of HPT rotor is shown in the Table 1. On the IPT rotor micro strains are obtained as 1.46 and 1.69. The load versus strain and maximum stress of IPT rotor is shown in the Table 2. The micro-strains on the LPT rotor are recorded as 0.90 and 0.93. The load versus strain and maximum stress of LPT rotor is shown in Table 3.

Table 1 Load vs. strain and maximum stress of HPT rotor

Groove no.	Load (N)	Strain (microns)	Max. stress (N/mm^2)
1	10	0.94	0.18
2	10	1.20	0.23
3	10	1.24	0.24

Table 2 Load vs. strain and maximum stress of IPT rotor

Groove no.	Load (N)	Strain (microns)	Max. stress (N/mm^2)
1	10	1.46	0.28
2	10	1.69	0.32

Table 3 Load vs. strain and maximum stress of LPT rotor

Groove no.	Load (N)	Strain (microns)	Max. stress (N/mm^2)
1	30	0.90	0.17
2	30	0.93	0.18

The static and dynamic loads on the turbine rotors are calculated. A source code has been developed to find out the bending moment at three grooves on HPT rotor, two grooves each on IP and LP rotors. Subsequently nominal stress is calculated to find out the stress concentration factors.

IV MODELING

The equivalent turbine rotors are modeled and analyzed using ANSYS. The chosen problem is considered as 2-D axi-symmetric problem to reduce the considerable time of computations and tedious computer efforts. Fig. 8 shows the Shell 63 element considered for meshing. Appropriate boundary conditions are incorporated in the analysis.

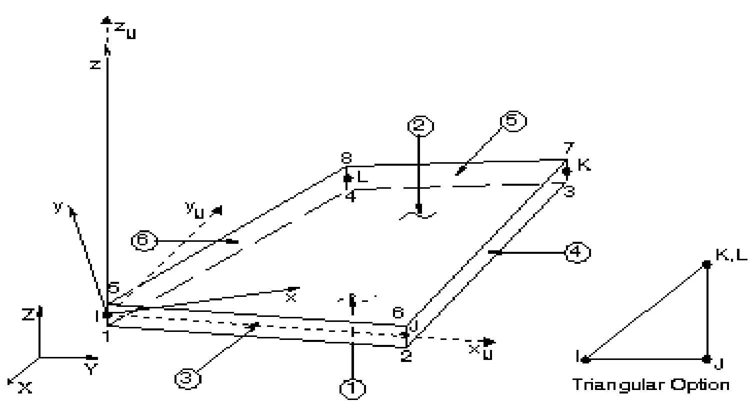

Fig. 8 Shell 63 element

The values obtained for nominal stress and maximum stress and theoretical stress concentration factors that of experimental and theoretical methods are given in Table 4, Table 5 and Table 6 for HPT, IPT and LPT rotors respectively. Fig.9, Fig.10 and Fig.11 show bending stress on HPT, IPT and LPT rotors respectively.

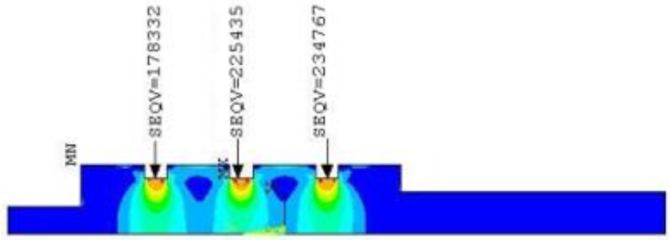

Fig. 9 Bending stress of HPT rotor

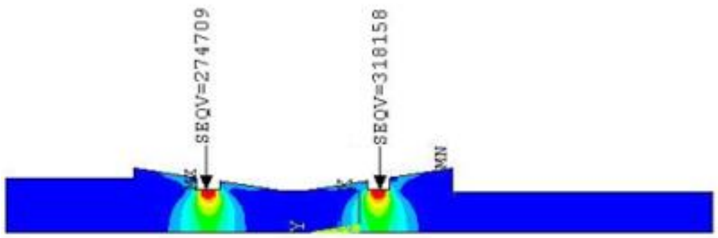

Fig. 10 Bending stress of HPT rotor

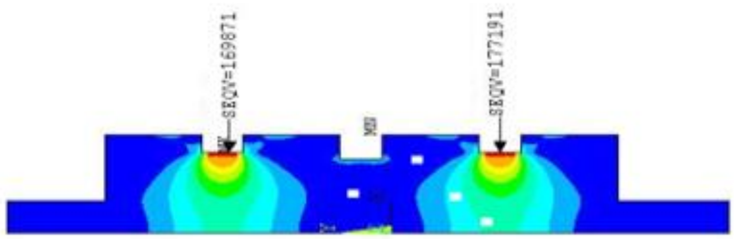

Fig. 11 Bending stress of HPT rotor

V DYNAMIC ANALYSES

Dynamic analysis of HPT, IPT and LPT rotors are carried out.

A. HPT Rotor

Dynamic stresses are computed by considering the load due to steam pressure. The load is considered as uniformly distributed load over a span of 1.712m of the HPT rotor. While evaluating dynamic stresses of HPT rotor, the effect of temperature is also considered.

The variation in dynamic stress versus dynamic stress concentration with respect to each groove for a particular temperature is plotted in Fig.12. The dynamic stress concentration factors corresponding to the dynamic stresses near each groove are tabulated in Table 7.

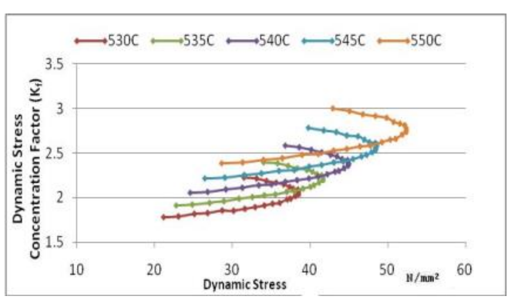

Fig. 12 Dynamic stress concentration factor based on dynamic stress

B. *IPT Rotor*

Dynamic stresses of IPT rotor are computed by considering the load due to steam pressure. The load is considered as uniformly distributed load over a span of 2.12m of the IPT rotor. While evaluating dynamic stresses, the effect of temperature is also considered.

The variation in dynamic stress versus dynamic stress concentration with respect to each groove for a particular temperature is plotted in Fig.13. The dynamic stress concentration factors corresponding to the dynamic stresses near each groove are tabulated in Table 8.

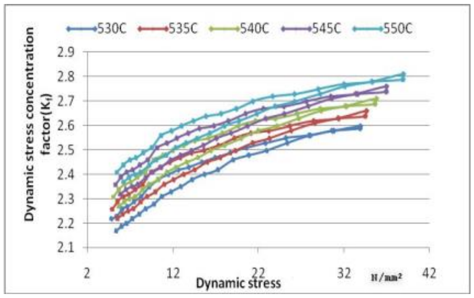

Fig. 13 Dynamic stress concentration factor based on dynamic stress

C. *LPT Rotor*

Dynamic stresses of LPT are computed by considering the load due to steam pressure. The load is considered as uniformly distributed load over a span of 2.52m of the LPT rotor. While evaluating dynamic stresses of the rotor, the effect of temperature is also considered.

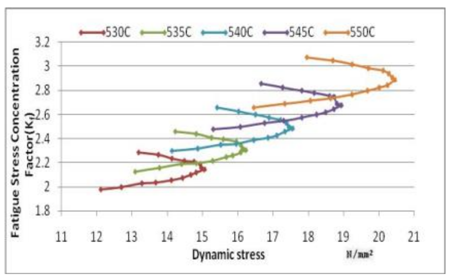

Fig. 14 Dynamic stress concentration factor based on dynamic stress

The variation in dynamic stress versus dynamic stress concentration with respect to each groove for a particular temperature is plotted in Fig.14.The dynamic stress concentration factors corresponding to the dynamic stresses near each groove are tabulated in Table 9.

VI. CONCLUSIONS

In the present work, an attempt has been made to investigate theoretically the effect of stress concentration near the groove sections of a steam turbine rotor system by considering HPT, IPT and LPT rotors. Results obtained theoretically are validated subsequently with experimental investigation carried-out on the prototypes of the rotors.

The conclusions are presented in two sections as stresses and stress concentration factors.

A. *Stresses on HPT Rotor*

It is observed that the dynamic stresses are increasing gradually from 1st groove and then decreasing to the last groove, that is, 25th. A peak value is observed near a groove located in the right half span of the rotor. It is further observed that there is a considerable increase in all the stresses near the last groove of the rotor compared to its 1st groove. As the temperature is increasing, stresses are also increasing.

Stresses on LPT Rotor

A similar trend is observed in the variation of stresses as that in HPT rotor. A peak value is observed near the groove at the middle of the span. But in contrast to the intensity of stress, there is a decrease in the magnitude of stress near the last groove to that of 1st groove. In this rotor also, stresses are increasing with increase in temperature.

B. Stresses on LPT rotor

In this rotor, the variation of stress is small from first to last groove section and it can be concluded that the stress intensity is same over the span of the groove section. A similar trend is observed for the thermal and dynamic stresses. A peak value is observed near the groove at the mid span.

In view of the above observations, it can be concluded that the intensity of stress can be minimized by reducing the reheat steam temperature, below the inlet steam temperature of 535^{0}C.

C. Stress concentration factors of HPT rotor based on dynamic stress

For the five temperatures considered for the theoretical investigation, the stress concentration factors are also increasing under dynamic load, that is, from 1.78 to 2.39, near the 1st groove, 2.07 to 2.78 near the 17th groove and 2.23 to 3.01 near the 25th groove.

D. Stress concentration factors of LPT rotor based on dynamic stress

For the five temperatures considered for the theoretical investigation, the stress concentration factors are also increasing under dynamic load that is from 2.17 to 2.49, near the 1st groove, 2.60 to 2.97 near the 21st groove and 2.22 to 2.52 near the 40th groove.

E. Stress concentration factors of LPT rotor based on dynamic stress

For the five temperatures considered for the theoretical investigation, the stress concentration factors are also increasing under dynamic load that is from 1.98 to 2.66, near the 1st groove, 2.15 to 2.89 near the 9th groove and 2.29 to 3.08 near the 16th groove.

From the above observations, it can be concluded that the intensity of vonmises stress is to be reduced which in turn lead to further reduction in the stress concentration factor. This problem can be overcome by providing the coats in the groove of the blades, which are having plastic deformation locally, during each overhaul regularly.

Experimental study taken-up on the proto types of the three rotors has resulted in similar study.

VII. FUTURE SCOPE

The work can be extended further considering twisting moment on the rotor for the rated power and speed. Further the stresses developed can also be computed considering the endurance strength of the rotor material. Stress concentration can also be estimated using the theories of failure, based on torsional and bending stresses.

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Table 4 Nominal stress, maximum stress and stress concentration factor of HPT rotor

Groove no.	Nominal stress (N/mm^2)	Experimental method		Theoretical method	
		Max. stress (N/mm^2)	Stress concentration factor(K_t)	Max. stress (N/mm^2)	Stress concentration factor(K_t)
1	0.08	0.18	2.14	0.18	2.12
2	0.10	0.23	2.16	0.23	2.13
3	0.11	0.24	2.19	0.23	2.17

Table 5 Nominal stress, maximum stress and stress concentration factor of IPT rotor

Groove no.	Nominal stress (N/mm^2)	Experimental method		Theoretical method	
		Max. stress (N/mm^2)	Stress concentration factor(K_t)	Max. stress (N/mm^2)	Stress concentration factor(K_t)
1	0.13	0.28	2.15	0.27	2.13
2	0.15	0.32	2.18	0.32	2.16

Table 6 Nominal stress, maximum stress and Stress concentration factor of LPT rotor

Groove no.	Nominal stress (N/mm^2)	Experimental method		Theoretical method	
		Max. stress (N/mm^2)	Stress concentration factor(K_t)	Max. stress (N/mm^2)	Stress concentration factor(K_t)
1	0.08	0.17	2.19	0.17	2.17
2	0.08	0.18	2.21	0.18	2.19

Table 7 Dynamic stress vs. dynamic stress concentration factor

Groove no.	Dynamic stress(N/mm^2)					Dynamic stress concentration factor(K_f)				
	530^0C	535^0C	540^0C	545^0C	550^0C	530^0C	535^0C	540^0C	545^0C	550^0C
1	21.04	22.72	24.52	26.44	28.57	1.78	1.92	2.06	2.22	2.39
2	22.98	24.81	26.77	28.97	31.29	1.79	1.93	2.07	2.23	2.40
3	25.06	27.02	29.12	31.48	33.98	1.82	1.95	2.10	2.26	2.43
4	26.76	28.85	31.22	33.73	36.37	1.83	1.96	2.12	2.28	2.45
5	28.62	30.82	33.32	35.96	38.90	1.86	1.99	2.14	2.31	2.49
6	30.07	32.52	34.98	37.89	40.96	1.86	2.01	2.15	2.32	2.50
7	31.54	34.08	36.79	39.82	43.00	1.88	2.03	2.18	2.35	2.53
8	32.87	35.50	38.30	41.42	44.71	1.90	2.04	2.20	2.37	2.55
9	34.07	36.94	39.81	43.02	46.39	1.92	2.07	2.22	2.40	2.58

10	35.14	37.89	40.99	44.26	47.71	1.94	2.08	2.24	2.41	2.59
11	36.05	39.03	42.18	45.50	49.18	1.95	2.11	2.27	2.44	2.63
12	37.00	40.00	43.19	46.55	50.27	1.98	2.13	2.30	2.47	2.66
13	37.43	40.46	43.67	47.23	50.98	1.99	2.14	2.31	2.49	2.67
14	38.06	41.10	44.32	47.89	51.82	2.02	2.17	2.33	2.51	2.71
15	38.35	41.56	44.77	48.34	52.27	2.04	2.20	2.36	2.54	2.74
16	38.47	41.49	44.85	48.40	52.30	2.05	2.21	2.38	2.56	2.76
17	38.49	41.58	44.91	48.42	52.32	2.07	2.23	2.40	2.58	2.78
18	38.36	41.47	44.75	48.38	52.18	2.10	2.26	2.43	2.62	2.82
19	37.77	40.82	44.04	47.60	51.49	2.11	2.27	2.44	2.63	2.84
20	37.34	40.31	43.45	46.92	50.72	2.13	2.3	2.47	2.66	2.86
21	36.54	39.58	42.63	46.15	49.84	2.15	2.32	2.49	2.69	2.9
22	35.54	38.32	41.42	44.66	48.37	2.17	2.33	2.51	2.70	2.92
23	34.35	37.16	40.12	43.38	46.78	2.19	2.36	2.54	2.74	2.94
24	33.08	35.76	38.57	41.67	45.05	2.22	2.39	2.57	2.76	2.98
25	31.46	33.98	36.77	39.69	42.87	2.23	2.40	2.59	2.79	3.01

Table 8 Dynamic stress vs. dynamic stress concentration factor

Groove no.	Dynamic stress (N/mm^2)					Dynamic stress concentration factors(K_f)				
	530^{0}C	535^{0}C	540^{0}C	545^{0}C	550^{0}C	530^{0}C	535^{0}C	540^{0}C	545^{0}C	550^{0}C
1	5.30	5.44	5.60	5.78	6.11	2.17	2.22	2.29	2.36	2.49
2	5.93	6.05	6.23	6.46	6.79	2.19	2.23	2.30	2.38	2.49
3	6.51	6.67	6.84	7.15	7.49	2.19	2.24	2.30	2.40	2.50
4	7.17	7.29	7.50	7.84	8.17	2.22	2.26	2.32	2.42	2.52
5	8.00	8.14	8.37	8.74	9.17	2.26	2.30	2.36	2.46	2.58
6	8.74	8.89	9.14	9.54	10.02	2.26	2.30	2.36	2.46	2.58
7	9.69	9.85	10.17	10.57	11.13	2.30	2.33	2.40	2.49	2.62
8	10.65	10.91	11.26	11.69	12.26	2.31	2.36	2.43	2.52	2.64
9	11.74	11.98	12.31	12.83	13.49	2.33	2.38	2.44	2.54	2.67
10	12.88	13.19	13.55	14.12	14.79	2.35	2.40	2.47	2.57	2.68
11	14.18	14.46	14.85	15.52	16.25	2.38	2.42	2.49	2.59	2.71
12	15.61	15.92	16.34	17.02	17.94	2.40	2.44	2.50	2.60	2.74
13	17.18	17.45	17.98	18.71	19.64	2.42	2.46	2.53	2.63	2.76
14	18.97	19.26	19.91	20.64	21.72	2.46	2.49	2.58	2.67	2.80
15	20.81	21.29	21.92	22.79	23.90	2.47	2.52	2.59	2.69	2.82
16	22.90	23.25	24.11	24.97	26.18	2.49	2.53	2.62	2.71	2.84
17	25.31	25.78	26.62	27.75	29.15	2.53	2.58	2.66	2.76	2.90
18	28.03	28.54	29.26	30.49	32.03	2.56	2.60	2.67	2.77	2.91
19	30.78	31.34	32.24	33.58	35.26	2.58	2.62	2.69	2.80	2.94
20	33.84	34.45	35.55	36.89	38.85	2.59	2.64	2.72	2.82	2.96
21	33.88	34.61	35.71	36.92	38.87	2.60	2.66	2.74	2.83	2.97
22	30.55	31.22	32.11	33.33	35.22	2.58	2.63	2.70	2.80	2.95

23	27.89	28.39	29.21	30.42	31.94	2.58	2.62	2.69	2.80	2.94
24	25.15	25.61	26.44	27.55	28.93	2.56	2.6	2.68	2.79	2.93
25	22.73	23.15	23.91	24.92	26.19	2.53	2.58	2.66	2.76	2.90
26	20.55	21.09	21.63	22.55	23.63	2.50	2.57	2.63	2.74	2.86
27	18.63	19.12	19.61	20.46	21.30	2.49	2.56	2.62	2.73	2.84
28	16.85	17.24	17.75	18.45	19.35	2.47	2.52	2.59	2.69	2.82
29	15.34	15.58	16.10	16.69	17.57	2.46	2.49	2.58	2.67	2.80
30	13.80	14.12	14.49	15.03	15.83	2.43	2.49	2.55	2.64	2.77
31	12.56	12.75	13.14	13.68	14.36	2.42	2.46	2.53	2.63	2.76
32	11.38	11.55	11.91	12.40	12.97	2.40	2.44	2.51	2.61	2.73
33	10.25	10.45	10.78	11.22	11.75	2.38	2.42	2.49	2.59	2.71
34	9.19	9.41	9.67	10.07	10.55	2.35	2.40	2.47	2.57	2.68
35	8.19	8.39	8.66	8.99	9.43	2.31	2.36	2.43	2.52	2.64
36	7.40	7.52	7.77	8.07	8.49	2.3	2.33	2.40	2.49	2.62
37	6.60	6.76	6.95	7.20	7.58	2.27	2.32	2.39	2.47	2.59
38	6.00	6.10	6.28	6.55	6.88	2.26	2.30	2.36	2.46	2.58
39	5.34	5.47	5.58	5.83	6.15	2.23	2.29	2.33	2.43	2.56
40	4.73	4.81	4.95	5.17	5.39	2.22	2.26	2.32	2.42	2.52

Table 9 Dynamic stress vs. dynamic stress concentration factor

S.No.	Dynamic stress(N/mm^2)					Dynamic stress concentration factor(K_f)				
	530^0C	535^0C	540^0C	545^0C	550^0C	530^0C	535^0C	540^0C	545^0C	550^0C
1	12.10	13.09	14.13	15.29	16.45	1.98	2.13	2.30	2.48	2.66
2	12.69	13.78	14.86	16.06	17.32	2.00	2.16	2.32	2.50	2.69
3	13.28	14.39	15.51	16.75	18.05	2.03	2.19	2.35	2.53	2.72
4	13.67	14.81	15.96	17.29	18.63	2.04	2.20	2.36	2.55	2.74
5	14.11	15.28	16.45	17.80	19.23	2.06	2.22	2.39	2.58	2.77
6	14.42	15.67	16.85	18.23	19.67	2.08	2.25	2.41	2.60	2.80
7	14.66	15.85	17.10	18.49	20.01	2.10	2.26	2.43	2.62	2.83
8	14.82	16.07	17.33	18.72	20.24	2.12	2.29	2.46	2.65	2.85
9	15.02	16.21	17.53	18.91	20.43	2.15	2.31	2.49	2.68	2.89
10	14.95	16.13	17.44	18.81	20.37	2.16	2.32	2.50	2.69	2.91
11	14.93	16.09	17.37	18.72	20.27	2.19	2.35	2.53	2.72	2.94
12	14.75	15.95	17.21	18.60	20.11	2.21	2.38	2.56	2.76	2.97
13	14.48	15.59	16.88	18.17	19.70	2.22	2.39	2.58	2.76	2.99
14	14.13	15.25	16.50	17.81	19.23	2.24	2.41	2.60	2.80	3.02
15	13.74	14.82	16.02	17.27	18.69	2.27	2.44	2.63	2.83	3.05
16	13.18	14.22	15.41	16.66	17.96	2.29	2.46	2.66	2.86	3.08