International Journal of scientific research and management (IJSRM)
||Volume||4||Issue||07||Pages||4371-4377||2016||
Website: www.ijsrm.in ISSN (e): 2321-3418

Analyse Forces Developed In Grinding Operation Of Bearing Races & Validate Spindle Used To Deliver Process Requirements

Devendra kumar Patel, Diplesh Gautam
M.Tech Scholar,
Department of Mechanical Engineering
Vindhya institute of technology and sciences
Satna, India
Email ID:devendra_satna11@rediffmail.com
Assistant Professor,
Department of Mechanical Engineering
Vindhya institute of technology and sciences
Satna, India
Email ID:dipleshgautam@yahoo.co.in

***Abstract*—Forces developed in grinding process are non-linear in nature, due to this non-linear functionality of forces vibration generates in spindles as well as whole machine. Spindle chosen for a particular operation is a very tedious job. The present research work was carried out to study to reduce the machine vibrations to minimum level so that production rates will be high with minimum cycle time.**

Keywords—deep groove ball bearing; equivalent chip thickness; spindle simulator; torque & power;

I. INTRODUCTION

A ball bearing is a type of rolling-element bearing that uses balls to maintain the separation between the bearing races.

The purpose of a ball bearing is to reduce rotational friction and support radial and axial loads. It achieves this by using at least two races to contain the balls and transmit the loads through the balls. In most applications, one race is stationary and the other is attached to the rotating assembly (e.g., a hub or shaft). As one of the bearing races rotates it causes the balls to rotate as well. Because the balls are rolling they have a much lower coefficient of friction than if two flat surfaces were sliding against each other.

Ball bearings tend to have lower load capacity for their size than other kinds of rolling-element bearings due to the smaller contact area between the balls and races. However, they can tolerate some misalignment of the inner and outer races.

There are several common designs of ball bearing, each offering various trade-offs. They can be made from many different materials, including: stainless steel, chrome steel, and ceramic (silicon nitride (Si3N4)). A hybrid ball bearing is a bearing with ceramic balls and races of metal.

In a deep-groove radial bearing, the race dimensions are close to the dimensions of the balls that run in it. Deep-groove bearings can support higher loads.

SKF deep groove ball bearings have deep, uninterrupted raceway grooves. These raceway grooves have a close osculation with the balls, enabling the bearings to accommodate radial and axial loads in both directions. These bearings are particularly versatile and are:

- Simple in design
- Non separable
- Suitable for high and even very high speeds
- Robust in operation, requiring little maintenance

Deep groove ball bearings are the most widely used bearing type. Consequently, they are available from SKF in many designs, variants, series and sizes.

SKF deep groove ball bearings are available for shaft diameters ranging from 3 to 1500 mm.

II. OBJECTIVE OF RESEARCH PAPER

The objective of the Research project is to:
- To Design of Integral Shaft Bearing for spindle
- Grinding Forces & power Calculations or different types of bearings
- Stress analysis and temperature distribution of Integral Shaft Bearing for spindle selection
- SKF Spindle Simulator software makes allowance for the effect of the operating speed and temperature on the bearing shaft and housing fits and also the bearing preload

III. Theory of Grinding Forces, Torque and Power

Formulas to calculate the tangential cutting force, torque and required machining power are the same as for other metal cutting operations (see Estimating Machining Power Section), but the values of Kc , specific cutting force or specific energy, are approximately 30 to 40 times higher in grinding than in turning, milling and drilling. This is primarily due to the fact that the ECT values in grinding are 1000 to 10000 times smaller, and also due to the negative rake angles of the grit. Average grinding rake angles are around –35 to –45 degrees.

Another difference compared to turning is the influence of the negative rake angles, illustrated by the ratio of FBHB/FBCB, where FBHB is the normal force and FBCB the tangential grinding force acting in the wheel speed direction. FBHB is much larger than the grinding cutting force.

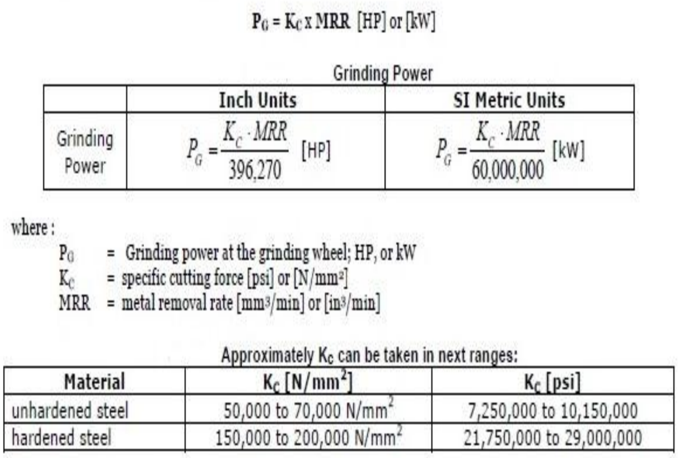
Generally FH/FC ratio is approximately 2 to 4.

It is apparent that both KC and FH/FC attain maximum values for given small values of ECT. This fact illustrates that forces and wheel-life are closely linked. For example, wheel speed has a maximum for constant wheel-life at approximately the same values of ECT. As a matter of fact, force relationships obey the same type of relationships as those of wheel-life. The information compiled in this section is intended as a guide in selecting the proper parameters for a particular grinding operation. The process of selecting the proper power, speed feed wheel etc., should be based on experience and testing. There are no general equation that can adequately describe the selection process without use of test results for the particular application.

A. Grinding Power

The relationship for the Grinding power calculation can be expressed as:

TABLE I. GRINDING POWER



$P_G = K_C \text{ x } MRR$ [HP] or [kW]

Grinding Power

	Inch Units	SI Metric Units
Grinding Power	$P_G = \frac{K_C \cdot MRR}{396{,}270}$ [HP]	$P_G = \frac{K_C \cdot MRR}{60{,}000{,}000}$ [kW]

where :

P_G = Grinding power at the grinding wheel; HP, or kW

K_C = specific cutting force [psi] or [N/mm²]

MRR = metal removal rate [mm³/min] or [in³/min]

Approximately K_C can be taken in next ranges:

Material	K_C [N/mm²]	K_C [psi]
unhardened steel	50,000 to 70,000 N/mm²	7,250,000 to 10,150,000
hardened steel	150,000 to 200,000 N/mm²	21,750,000 to 29,000,000

The grinding cutting forces are relatively small because chip area is very small.

As in the other metal cutting operations, the forces vary with **ECT** - equivalent chip thickness and to a smaller extent with the wheel speed **V**.

B. ECT – Equivalent chip thickness in Grinding

The definition of ECT is: ECT = A/CEL in [mm] or [inch]

Where: A- cross sectional area of cut (approximately = feed x depth of cut) – [mm^2] or [inch^2]

CEL – cutting edge length (tool contact rubbing length) in [mm] or [inch]

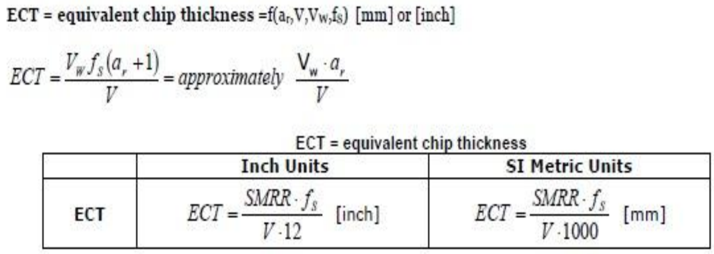
In turning, milling and drilling, ECT varies between 0.05 and 1 mm, and is always less than the feed/rev o feed/tooth; its value is usually about 0.7 to 0.9 times the feed. ECT is much smaller in grinding than in milling, ranging from about 0.0001 to 0.001 mm (0.000004 to 0.00004 inch).

In turning and milling, ECT is defined as the volume of chips removed per unit cutting edge length per revolution of the work or cutter. In milling specifically, ECT is defined as:

$$ECT = \frac{\pi \cdot D \cdot z \cdot f_z \cdot a_r \cdot a_a}{CEL}$$

In grinding, the same definition of ECT applies if we replace the number of teeth with the average number of grits along the wheel periphery, and replace the feed per tooth by the average feed per grit. This definition is not very practical, however, and ECT is better defined by the ratio of the specific metal removal rate - SMMR, and the wheel speed - V. Keeping ECT constant when varying SMRR requires that the wheel speed must be changed proportionally. In milling and turning ECT can also be redefined in terms of SMRR divided by the work and the cutter speeds respectively, because SMRR is proportional to the feed rate FBRB.

TABLE II. EQUIVALENT CHIP THICKNESS



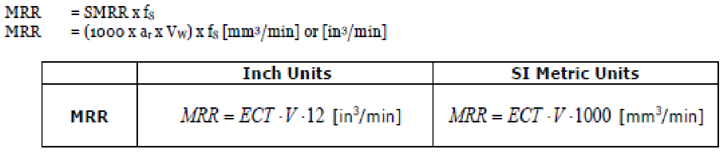
ECT = equivalent chip thickness =f(a_r,V,V_W,f_S) [mm] or [inch]

$$ECT = \frac{V_W f_S (a_r + 1)}{V} = approximately\ \frac{V_w \cdot a_r}{V}$$

ECT = equivalent chip thickness

	Inch Units	SI Metric Units
ECT	$ECT = \frac{SMRR \cdot f_S}{V \cdot 12}$ [inch]	$ECT = \frac{SMRR \cdot f_S}{V \cdot 1000}$ [mm]

TABLE III. MATERIAL REMOVAL RATE



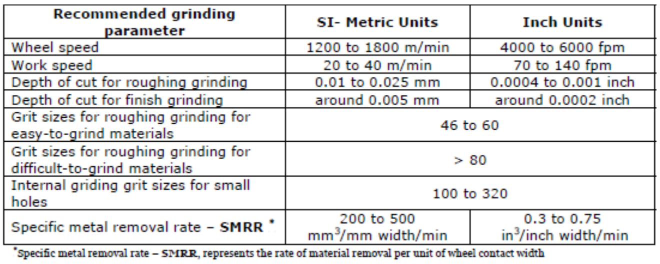
MRR = SMRR x f_S

MRR = (1000 x a_r x V_W) x f_S [mm³/min] or [in³/min]

	Inch Units	SI Metric Units
MRR	$MRR = ECT \cdot V \cdot 12$ [in³/min]	$MRR = ECT \cdot V \cdot 1000$ [mm³/min]

Grinding data are scarely available in handbooks, which usually recommend a small range of depth and work speeds at constant wheel speed, including small variations in wheel and work material composition. Wheel life or grinding stiffness are seldom considered.

TABLE IV. GRINDING PARAMETER



Recommended grinding parameter	SI- Metric Units	Inch Units
Wheel speed	1200 to 1800 m/min	4000 to 6000 fpm
Work speed	20 to 40 m/min	70 to 140 fpm
Depth of cut for roughing grinding	0.01 to 0.025 mm	0.0004 to 0.001 inch
Depth of cut for finish grinding	around 0.005 mm	around 0.0002 inch
Grit sizes for roughing grinding for easy-to-grind materials	46 to 60	
Grit sizes for roughing grinding for difficult-to-grind materials	> 80	
Internal griding grit sizes for small holes	100 to 320	
Specific metal removal rate – **SMRR** *	200 to 500 mm³/mm width/min	0.3 to 0.75 in³/inch width/min

*Specific metal removal rate – SMRR, represents the rate of material removal per unit of wheel contact width

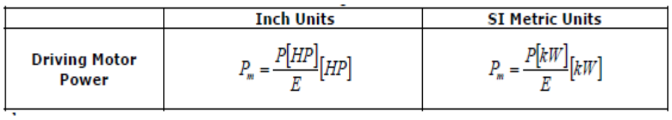
C. The driving motor characteristics

The machine tool transmits the power from the driving motor to the workpiece where it is used to cut the material. The effectiveness of this transmission is measured by the **machine tool efficiency factor E.**

- **Driving Motor Power**

The Power at the Driving motor, for all kind of machining is given below:

TABLE V. DRIVING MOTOR POWER



	Inch Units	SI Metric Units
Driving Motor Power	$P_m = \frac{P[HP]}{E}[HP]$	$P_m = \frac{P[kW]}{E}[kW]$

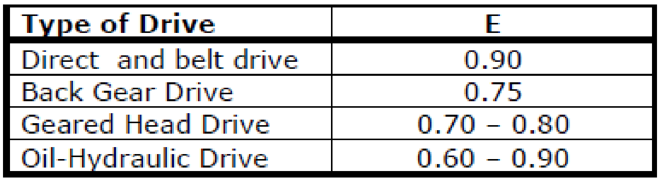
Where:

P = power at the cutting tool; HP, or kW

P_m = power at the motor; HP, or kW

E = machine tool efficiency factor

TABLE VI. E VALUE FOR TYPE OF DRIVES

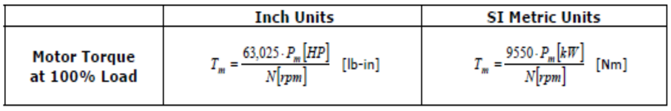


Type of Drive	E
Direct and belt drive	0.90
Back Gear Drive	0.75
Geared Head Drive	0.70 – 0.80
Oil-Hydraulic Drive	0.60 – 0.90

- **Driving Motor Torque**

Separate formulas are required for use with customary inch units and for SI metric units:

TABLE VII. MOTOR TORQUE



	Inch Units	SI Metric Units
Motor Torque at 100% Load	$T_m = \frac{63{,}025 \cdot P_m[HP]}{N[rpm]}$ [lb-in]	$T_m = \frac{9550 \cdot P_m[kW]}{N[rpm]}$ [Nm]

Where:

T_m – motor torque [lb-in] or [Nm]

P_m – motor power [HP] or [kW]

N – motor rotational speed [rpm]

IV. SKF Spindle Simulator

SKF Spindle Simulator is an advanced simulation software program for the analysis of spindle applications. Based on the SKF Simulator platform and using the same advanced technology, it has been designed to be exceptionally user friendly. The software makes allowance for the effect of the operating speed and temperature on the bearing shaft and housing fits and also the bearing preload. In addition, at each point in the spindle's duty cycle, it analyzes the effect of the external loads on the shaft and the bearings and delivers highly accurate information about each contact for each rolling element on each bearing. SKF has combined SNFA and SKF's engineering knowledge and resulted in the development of this software program. This program supports the analysis of spindles and contains detailed models of the new harmonized SKF-SNFA super-precision bearings.

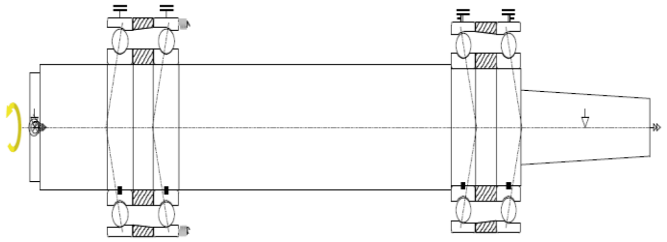


Fig. 1. Spindle system

Functionality

- All super-precision bearings
- Shaft deflection graphs
- Mounting analysis (preload, shaft and housing fits etc.)
- Input axial temperature distribution for shaft and housing (z-direction) in the 2D drawing area
- Lubrication and material database
- Gravity direction setting possible
- Expected fatigue life of the bearings
- Electric motor rotor component
- Speed limits

Benefits

- This software program combines engineering experience from SKF and SNFA.
- This program helps the building of spindle models in a fast and user friendly way.
- It includes all types of SKF-SNFA super-precision bearings (angular contact ball bearings, cylindrical roller bearings, double row cylindrical roller bearings and double direction angular contact thrust ball bearings).
- Based on the SKF Simulator platform and delivers highly accurate results.
- 3D animations show just how the spindle is operating.
- Report templates are available in the program and their export provides easy report generation.
- Clear self-explanatory documentation.
- The SKF Spindle Simulator makes an easy link between the user and SKF's engineering knowledge.

V. Grinding Forces & Power Calculation

- P = Ft * Vs
  Where
  Vs = Cutting Speed (m/s)
  P = Grinding Power (W)
  Ft = Tangential Grinding Force (N)
- Vs = pi() * ds * ns / 60000
  Where
  ds = Grinding Wheel Dia (mm)
  ns = Grinding Wheel rpm
- Ft = F't * bd
  Where
  F't = Specific Tangential Force (N/mm)
  bd = Active Grinding Wheel Width (mm)

- F't = F1 * (heq)d
  Where
  F1 = Specific Tangential Force at heq = 1 µm (N/mm)

  d = Constant (0.6 < d < 0.9)
- heq = pi() * dw * f / (Vs * 1000)
  Where
  dw = Workpiece Dia.
  f = Radial feed rate
  bd = [2 * r * (cos-1(r-((dk-de)/2)/r)] + length of land
- Torque = (power*60000)/(2*pi*rpm)

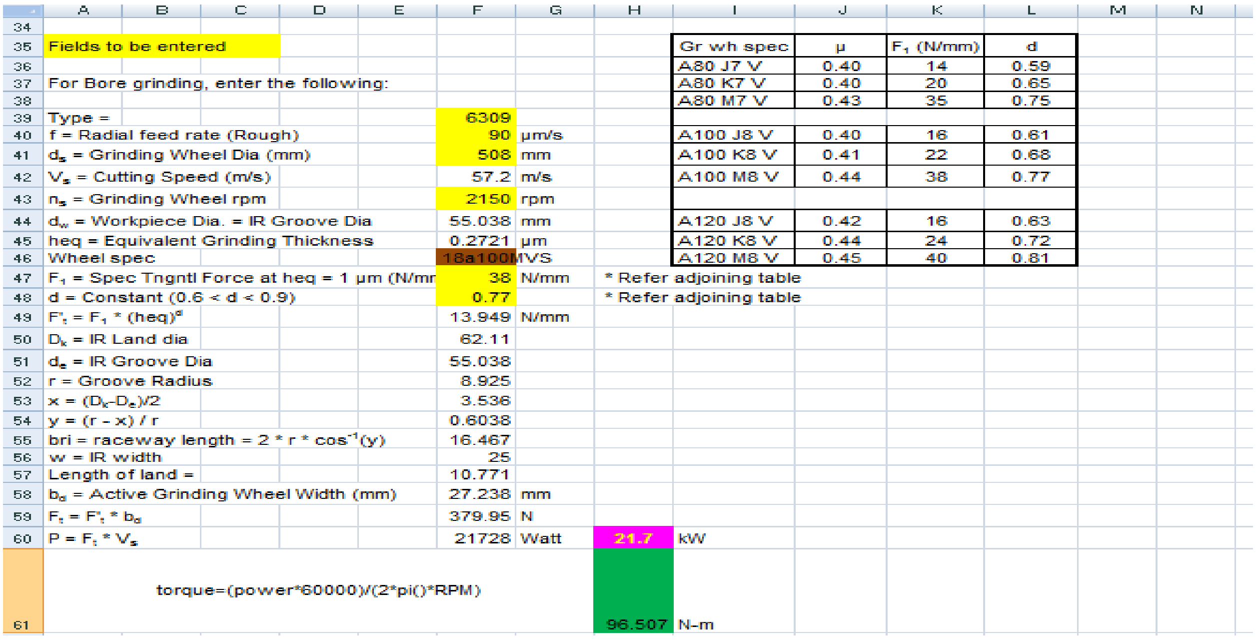
A. *Calculations for bearing type 6309*

- F (radial feed rate) = 90 µm/s
- Ds (Grinding Wheel Dia) = 508 mm
- Vs (Cutting Speed) = pi* ds * ns / 60000 = pi*508*2150/60000 = 57.2 m/s
- Ns (Grinding Wheel rpm) = 2150 rpm
- Dw (Workpiece Dia. = IR Groove Dia) = 55.038 mm
- Heq (Equivalent Grinding Thickness) = pi * dw * f / (Vs * 1000)

= pi*55.038*90/(57.2*1000) = 0.2721 µm

- F1 (Spec Tngntl Force at heq = 1 µm (N/mm)) = 38 N/mm
- D (Constant (0.6 < d < 0.9)) = 0.77
- F't = F1 * (heq)^d = 38*(0.2721)^0.77 = 13.949 N/mm
- Dk (IR Land dia) = 62.11 mm
- De (IR Groove Dia) = 55.038 mm
- r (Groove Radius) = 8.925
- x = (Dk-De)/2 = 62.11-55.038/2 = 3.536 mm
- y = (r - x) / r = 0.6038
- bri (raceway length) = 2 * r * cos-1(y) = 16.467 mm
- w (IR width) = 25 mm
- Length of land = 10.771 mm
- bd (Active Grinding Wheel Width) = length of land + bri
- Ft = F't * bd = 379.95 N
- P = Ft * Vs = 21.7 KW
- Torque = (power*60000)/(2*pi*RPM) = 96.507 N-m

B. *Calculations for bearing type 6309 in Microsoft Excel*



	A	F	G	H	I	J	K	L	M	N
34										
35	Fields to be entered				Gr wh spec	µ	F_1 (N/mm)	d		
36					A80 J7 V	0.40	14	0.59		
37	For Bore grinding, enter the following:				A80 K7 V	0.40	20	0.65		
38					A80 M7 V	0.43	35	0.75		
39	Type =	6309								
40	f = Radial feed rate (Rough)	90	µm/s		A100 J8 V	0.40	16	0.61		
41	d_s = Grinding Wheel Dia (mm)	508	mm		A100 K8 V	0.41	22	0.68		
42	V_s = Cutting Speed (m/s)	57.2	m/s		A100 M8 V	0.44	38	0.77		
43	n_s = Grinding Wheel rpm	2150	rpm							
44	d_w = Workpiece Dia. = IR Groove Dia	55.038	mm		A120 J8 V	0.42	16	0.63		
45	heq = Equivalent Grinding Thickness	0.2721	µm		A120 K8 V	0.44	24	0.72		
46	Wheel spec	18a100M	VS		A120 M8 V	0.45	40	0.81		
47	F_1 = Spec Tngntl Force at heq = 1 µm (N/mr	38	N/mm	* Refer adjoining table						
48	d = Constant (0.6 < d < 0.9)	0.77		* Refer adjoining table						
49	$F'_t = F_1 * (heq)^d$	13.949	N/mm							
50	D_k = IR Land dia	62.11								
51	d_e = IR Groove Dia	55.038								
52	r = Groove Radius	8.925								
53	$x = (D_k-D_e)/2$	3.536								
54	y = (r - x) / r	0.6038								
55	bri = raceway length = 2 * r * $\cos^{-1}(y)$	16.467								
56	w = IR width	25								
57	Length of land =	10.771								
58	b_d = Active Grinding Wheel Width (mm)	27.238	mm							
59	$F_t = F'_t * b_d$	379.95	N							
60	$P = F_t * V_s$	21728	Watt	21.7	kW					
61	torque=(power*60000)/(2*pi()*RPM)			96.507	N-m					

Similar type of bearing calculations has been done on another bearings i,e. bearing type 6309, 6310, 6211, 6311, 6212, 6312, 6213, 6313 at different feed rates.

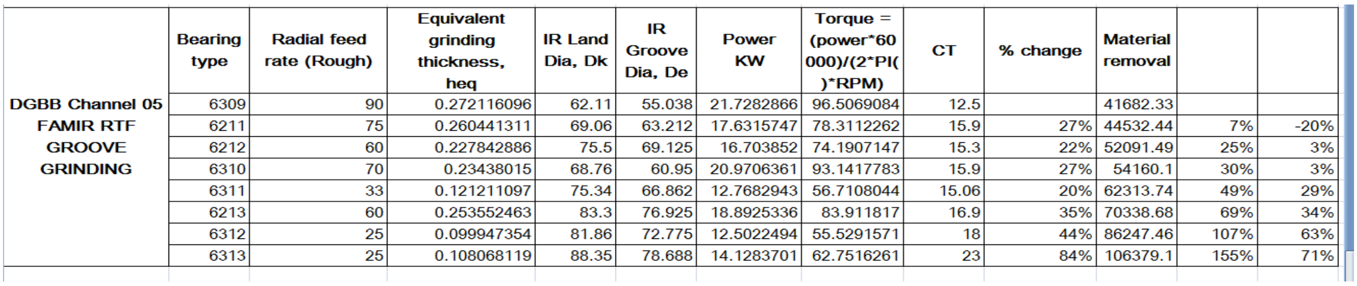
VI.RESULTS & DISCUSSION

Various process parameters calculations in tabulated form

TABLE VIII. VARIOUS PROCESS PARAMETERS ANALYSIS FOR PARTICULAR BEARING TYPE (1)

	Bearing Type	Radial Feed Rate (Rough)	Equivalent Grinding Thickness, heq	IR land Dia, Dk	IR Groove Dia, De	Power KW	Torque =(power*60000/2*pi*RPM)	CT	Material removal
DGBB Channel 05 FAMIR RTF Groove Grinding	6313	**25**	0.108068119	88.35	78.688	14.1283701	62.7516261	**23**	106379.139
	6213	60	0.253552463	83.3	76.925	18.8925336	83.911817	16.9	70338.677
	6312	**25**	0.099947354	81.86	73.775	**12.5022494**	55.5291571	18	86247.463
	6212	60	0.227842886	75.5	69.125	16.703852	74.1907147	15.3	52091.492
	6311	33	0.121211097	75.34	66.862	12.7682943	56.7108044	15.06	62313.74
	6211	75	0.260441311	69.06	63.212	17.6315747	78.3112262	15.9	44532.437
	6310	70	0.23438015	68.76	60.95	20.9706361	93.1417783	15.9	54160.097
	6309	**90**	0.272116096	62.11	55.038	**21.7282866**	96.5069084	**12.5**	41682.325

TABLE IX. VARIOUS PROCESS PARAMETERS ANALYSIS FOR PARTICULAR BEARING TYPE (2)



	Bearing type	Radial feed rate (Rough)	Equivalent grinding thickness, heq	IR Land Dia, Dk	IR Groove Dia, De	Power KW	Torque = (power*60000)/(2*PI()*RPM)	CT	% change	Material removal		
DGBB Channel 05 FAMIR RTF GROOVE GRINDING	6309	90	0.272116096	62.11	55.038	21.7282866	96.5069084	12.5		41682.33		
	6211	75	0.260441311	69.06	63.212	17.6315747	78.3112262	15.9	27%	44532.44	7%	-20%
	6212	60	0.227842886	75.5	69.125	16.703852	74.1907147	15.3	22%	52091.49	25%	3%
	6310	70	0.23438015	68.76	60.95	20.9706361	93.1417783	15.9	27%	54160.1	30%	3%
	6311	33	0.121211097	75.34	66.862	12.7682943	56.7108044	15.06	20%	62313.74	49%	29%
	6213	60	0.253552463	83.3	76.925	18.8925336	83.911817	16.9	35%	70338.68	69%	34%
	6312	25	0.099947354	81.86	72.775	12.5022494	55.5291571	18	44%	86247.46	107%	63%
	6313	25	0.108068119	88.35	78.688	14.1283701	62.7516261	23	84%	106379.1	155%	71%

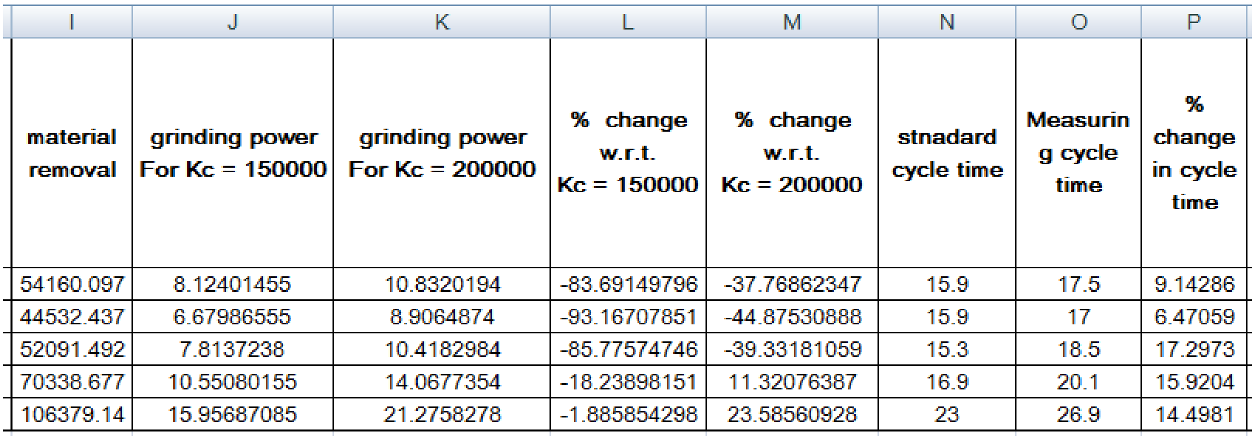
As we seen from the above tables with increasing radial feed rate power and torque increasing and correspondingly the cycle time for the particular bearing type decreases. As CT reduces the material removal rates also decreases. For bearings type 6313, at radial feed of 25 µm/s, power value is greater than that of bearing type 6312 at same radial feed rate because of IR groove diameter in case of bearing type 6313 is greater than bearing type 6312, so IR groove dia is one of the important parameter for selecting the spindle for particular bearing type.

Bearing analysis

TABLE X. VARIOUS PROCESS PARAMETERS ANALYSIS FOR PARTICULAR BEARING TYPE (3)

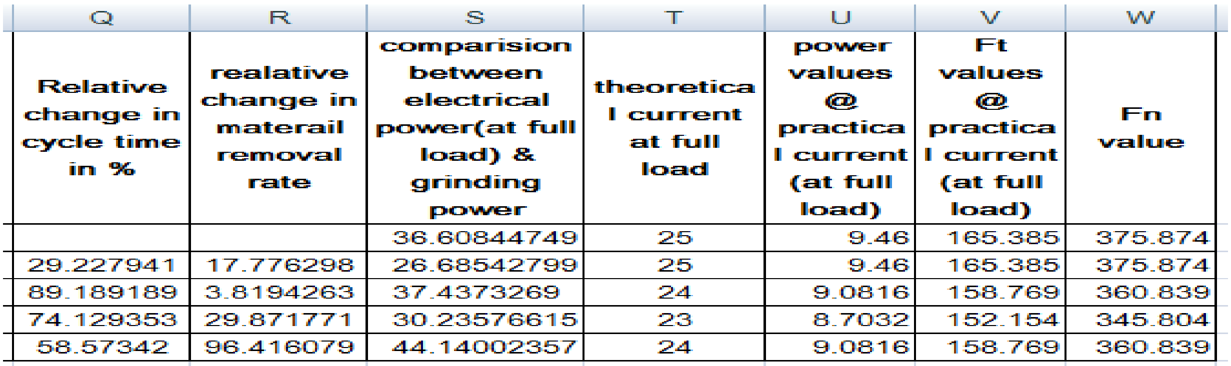
	Bearing Type	Shoulder Diameter	Grinding Power(Theoretical Power)	Current In amp (at full load)	Current In amp (at no load)	Electrical Power at Full Load	Electrical Power at No Load
DGBB Channel 05 FAMIR RTF Groove Grinding	6310	68.76	14.92312	25	19	9.46	7.1896
	6211	69.06	12.9033	25	19	9.46	7.1896
	6212	75.5	14.516	24	18	9.0816	6.8112
	6213	83.3	12.47516	23	18	8.7032	6.8112
	6313	88.35	16.25779	24	19	9.0816	7.1896

TABLE XI. VARIOUS PROCESS PARAMETERS ANALYSIS FOR PARTICULAR BEARING TYPE (4)



I	J	K	L	M	N	O	P
material removal	grinding power For Kc = 150000	grinding power For Kc = 200000	% change w.r.t. Kc = 150000	% change w.r.t. Kc = 200000	stnadard cycle time	Measuring cycle time	% change in cycle time
54160.097	8.12401455	10.8320194	-83.69149796	-37.76862347	15.9	17.5	9.14286
44532.437	6.67986555	8.9064874	-93.16707851	-44.87530888	15.9	17	6.47059
52091.492	7.8137238	10.4182984	-85.77574746	-39.33181059	15.3	18.5	17.2973
70338.677	10.55080155	14.0677354	-18.23898151	11.32076387	16.9	20.1	15.9204
106379.14	15.95687085	21.2758278	-1.885854298	23.58560928	23	26.9	14.4981

TABLE XII. VARIOUS PROCESS PARAMETERS ANALYSIS FOR PARTICULAR BEARING TYPE (5)



Q	R	S	T	U	V	W
Relative change in cycle time in %	realative change in materail removal rate	comparision between electrical power(at full load) & grinding power	theoretical current at full load	power values @ practical current (at full load)	Ft values @ practical current (at full load)	Fn value
		36.60844749	25	9.46	165.385	375.874
29.227941	17.776298	26.68542799	25	9.46	165.385	375.874
89.189189	3.8194263	37.4373269	24	9.0816	158.769	360.839
74.129353	29.871771	30.23576615	23	8.7032	152.154	345.804
58.57342	96.416079	44.14002357	24	9.0816	158.769	360.839

As concluded from the bearing analysis, dereasing the current at full load keeping the electrical current at no load at constant value, with increasing shouler diameter the grinding power also increases, so electrical current is one of the important parameter regarding selecting tha appropriate spindle for the process grinding power for Kc = 150000 & Kc = 200000 both increases with decrease in current at full load and increase in current at no load and due to this percentage change in cycle time also increases.

Skf spindle simulator requirement analysis: Theoretical Bearing Life (Main Operating Condition):

Bearing	Basic Rating Life[h]	SKF Rating Life (GC5000)[h]	DIN ISO 281 addendum 4 - 2003[h]
<Component.ShaftSystem_1>7214 CD_2	400618	> 1 000 000	> 1 000 000
<Component.ShaftSystem_1>s7214 CD	262844	> 1 000 000	> 1 000 000
<Component.ShaftSystem_1>s7215 CD	> 1 000 000	> 1 000 000	> 1 000 000
<Component.ShaftSystem_1>s7215 CD_2	400613	> 1 000 000	> 1 000 000
L_system	120073	> 1 000 000	> 1 000 000

As seen from the above table, angular contact ball bearing 7214 CD has minimum life hours although it has sufficient life to running with the corresponding spindle rpm and environment around the spindle system. The whole system has a satisfactory life hours of 120073. So system in safe mode under these forces.

- **Vibration analysis**

Spindle system is not affected by vibration due to spindle rpm is very less w.r.t. first vibrating mode of frequency which is around 9000 rpm, so system is safe.

With these considerations we can improve the vibration performance of the spindle. With the help of cambell diagram we can find the modes of resonating frequencies.

Considerations:

Spring preload of bearing = 2080 N

Tangential Cutting force = 165 N

Axial Cutting force = 0.25 x Ft = 41.25 N

Radial force = 375.8 N

VI. CONCLUSIONS

- Radial feed rate directly proportional to grinding power and torque.
- As radial feed rate increases the mean cycle time for particular bearing decreases.
- Forces and vibration within the permissible limit does not affect the spindle system.
- Angular contact ball bearings is slightly preloaded because it ensures higher rigidity and reduced noise and increase the accuracy of the spindle system.

References

[1] N. Tandon, A. Choudhury, A Review of Vibration and Acoustic Measurement Methods for the Detection of Defects in Rolling Element Bearings, Tribology International, 32 (1999), pp. 469–480.

[2] P.D. McFadden, J.D. Smith, The Vibration Produced by Multiple Point Defect in a Rolling Element Bearing, Journal of Sound and Vibration, 98 (1985), pp. 263–273.

[3] V. N. Patel, N. Tandon , R. K. Pandey, 2010. A Dynamic Model for Vibration Studies of Deep Groove Ball Bearings Considering Single and Multiple Defects in Races, Journal of Tribology Transaction of ASME 132, p. 041101-1-041101-10.

[4] ON Sud, PB Davies, J Halling,Thermal-behavior of rolling bearing assemblies subjected to preload Wear, 27 (1974), pp. 237–249.

[5] A Palmgren, B Ruley, Ball and roller bearing engineering, SKF Industries, inc., Philadelphia (1945) SKF Industries inc.

[6] SKF General Catalogue. 2003.

[7] K Nakajima, Thermal contact resistance between balls and rings of a bearing under axial, radial, and combined loads, Journal of Thermophysics and Heat Transfer, 9 (1995), pp. 88–95.

[8] MM Khonsari, ER Booser, Applied tribology: bearing design and lubrication (2nd ed.)Wiley, Chichester, England; Hoboken, NJ (2008).

[9] SKF spindle simulator software version 2.3

[10] W. Jacobs, R. Boonen, P. Sas, D. Moens, The influence of the lubricant film on the stiffness and damping characteristics of a deep groove ball bearing, Mech. Syst. Signal Process., 42 (1–2) (2014), pp. 335–350.