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"Design and analysis of spindle head for micro milling machine"

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Abstract: *We are well known of phrase "World is becoming so smaller" i.e. the current era is of micro parts and the sizes of the parts are reducing day by day. On the other hand these small parts required to be manufactured with great accuracy and high surface finish. Usually these complex, three dimensional shapes are manufactured with the special milling machine called micro milling. The problems associated with micro milling are, increase in spindle run out & its vibrations with increase in speed. Also, critical design of high speed bearings & drive system adds to its complex nature. Thus challenge lies with controlling the stated noise factors. It is proposed to have friction disc drive for micro milling machine spindle. In the present work the emphasis is laid on controlling the spindle run out by proper design. Also, analysis of spindle by FEM (Finite element method) is undertaken. The results obtained for designed spindle under stipulated conditions of cutting force (3-7 N) are motivating. The maximum run out for spindle in this case found to be 20μ & minimum is 13μ. The analysis carried out takes in to account the linear as well as non linear aids. The speed adopted in current case is in the range of 1600 to 9600 rad/sec. However it is recommended to use speed in the range of 4000 to 4800 rad/sec. the stiffness of air bearing is kept in the range of* 8×10^4 *to* 8.8×10^5 *N/m. it is recommended to keep stiffness of air bearing between* 5.2×10^5 *to* 7.2×10^5*. The diameter of tool shank must be in the range of 2.5 to 3.2mm. Length of tool shank is to be kept in between 38 to 50mm & the tool with young's* 6.8×10^{11} *N/m*^{2} *must be used so as to have minimum spindle run out.*

Key words: *contact stress, drive system, micro milling, and spindle run out.*

I. Introduction

The technology used for producing micro scale three dimensional components is called micro milling. Micro milling is similar to conventional milling process. But, the produced features are in micro scale. Due to use of micro tool this milling process differs from conventional milling process in variety of factors (i.e. cutting forces, material removal rate, spindle speed & tool run out). For manufacturing this high precision machine, drive system, spindle unit & bearings used are different than conventional milling machines. Because, if small error is tolerated it will lead to major dimensional inaccuracy in produced component.

Micro milling is applicable in electro optics, automotive, biotechnology, aerospace, information technology & medical. Micro milling has ability to machine wide range of materials & to produce complex three dimensional shapes. The material used is selected as per the application e.g. optical components are made from polymer, glass or aluminum. Automotive components are made from several ferrous & non ferrous materials, alloys. Some mechanical components have requirement of submicron accuracy & nanometer surface finish. For this, mechanical micro machining is suitable process [01].

II. Literature review

Researchers worked on various aspects of micro milling. Such as, run out measurement, cutting force measurement, high speed bearings, machining on various metals, modeling approaches & reduction in process time.

Dynamic design & modeling approach is used for analysis & optimization of overall machine dynamic performance at the beginning of designing the machine [1]. Experimental & modeling studies on micro milling of AL2024-T6 aluminum & AISI4340 steel has been carried out [8]. The series of cutting tests for variable cutting speed, feed, and depth of cut were performed to verify frictional vibrations. Test results shown that quality of surface decreases as depth of cut increases. Cutting parameters has impact on surface quality & vibrations generated in machine [9]. Bearing stiffness & damping coefficients calculated numerically to determine threshold rotor mass under various operating conditions. The bearing used for this experiment was multi array orifice feeding bearings & porous air journal bearings [6]. A miniature milling spindle with Active Magnetic Bearings (AMBs) was built. A rotor dynamic model was developed to expedite the controller design & made it possible to predict spindles performance under the influence of cutting forces. The spindle used has ability to reach the speed of 1, 50,000 rpm. The paper concludes that, to increase the rotational speed, rotor diameter has to be reduced [7]. An experimentation on 7 kg 460mm long & 50mm diameter rotor was carried out to understand its mechanical & thermal behavior, the set up is capable of loading the rotor axially & radialy in static & dynamic conditions. The test carried out at 60,000 rpm. Initial testing's carried out in static & dynamic conditions with no whirl instability. Also, the scope is placed to work in rotor stability & dynamic stiffness [5, 16]. Measurement of radial motions at two axial locations is done. For this, the laser Doppler vibrometer with precision cylindrical artifract were used. The radial motion is measured & then processed to obtain radial & tilt error motions. Alignment procedure is suggested to ensure mutual perpendicularity of X & Y laser beams [4]. Force measurement in micro milling is carried out, the experimental set up consist of 3 axis vertical milling machine with positioning repeatability of 1 micron along all axes is used. The peak value of force obtained in all direction is lower than 0.25N [23]. New model for estimation of cutting forces based on specific cutting pressure in micro milling was generated [2]. Design, assembly & testing of Ultra High speed micro milling spindle is done. Milling machines with friction disc drive to transmit power to tool is used to carry an experiment. In this case the tool shank is attached with friction disc & supported by porous air journal bearing. The friction disc shows excessive run out with increase in rpm. The spindle speed greater than 20,000 rpm produces contact of tool shank & inner surface of bearing. It is also claimed that the spindle is also capable of running at 5, 00,000 rpm.

III. Design Of Spindle

This includes design calculations of "Air Bearing & Friction Disc Drive", Models of parts of Spindle unit with the help of CATIA as per the designed dimensions. Validation of the design by FEM is also discussed.

3.1 Factors affecting performance of spindle for micro milling machine

In order to find out effect of various parameters on run out of spindle cause effect study is carried out. The parameters are as shown in Fig.3.1.

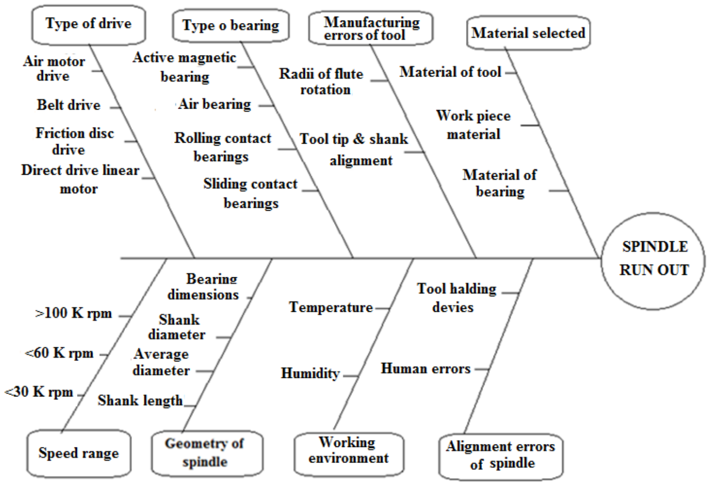

Fig.3.1 Cause effect diagram for spindle run out.

Table. 3.1 Selection of parameters & components for spindle head assembly

Sr. no.	Component/Parameter	Selection	Reason for selection
1.	Drive for spindle	Friction disc drive	High drive ratio can be obtained from Friction disc drive
2.	Tool material	Carbide tool	High hardness over wide range of temperature (up to 900˚C), very stiff & low thermal expansion [13].
3.	Bearing	Multi array orifice air bearing	These bearings have high load bearing capacity (up to 300N) as compared with porous journal bearings (load bearing capacity up to 10N) [5, 10].
4.	Work piece material	Aluminum	Good machinabily & wide range of applications.
5.	Speed range	70,000 rpm to 90,000 rpm	The cutting speed required for tool & work piece combination is 220m/min to 282m/min.

Comment -

- As number of parts in spindle assembly increases the manufacturing errors associated with each part will lead to run out of spindle. Hence to reduce run out number of parts are to be reduced. This will also reduce alignment errors.

- Less number of parts lead to less friction & less heat generation. As bearings are sensitive to temperatures, reduction in parts will reduce heat generated during operation.
- Air bearings can be utilized for small values of loads.
- For reduction of weight conventional tool holding & drive system cannot be used.
- The effective way to tackle this problem is to use tool shank itself as a spindle, supported in air bearings & driven by friction disc.

Such spindle exists, in work carried out by J.P.Pathak. The assembly is as shown in fig. 3.3.

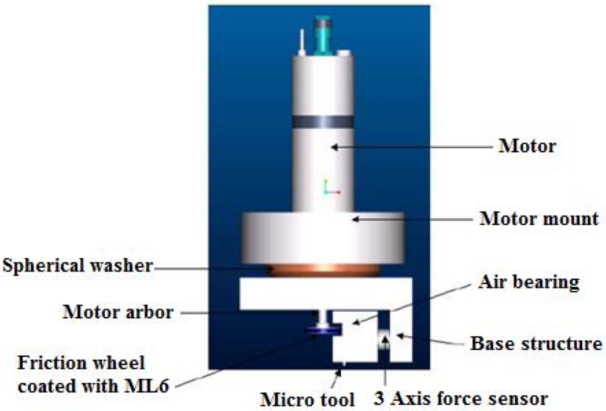

Fig.3.3 Solid model of ultra-high speed micro-milling spindle system [10].

Fig. 3.3 shows micro milling spindle with porous air journal bearing. The base plate holds all the components in their place. The motor is mounted on motor mount which is attached to base. The motor arbor, friction wheel & ML6 polymer coating are coaxial. The air bearing is attached to another face of base structure. In which, tool shank is inserted & is held in position by friction disc. To the back side of air bearing 3 axis force sensor is mounted which measures cutting forces in X, Y & Z direction. The friction disc rotates in contact with the tool shank. The main advantage of this arrangement is less number of components which gives reduced weight & reduced centrifugal forces which leads to less radial displacement of the tool.

3.2 Design calculations of spindle

After reading the literature available on micro milling & doing cause effect study, design of micro milling spindle is proposed as shown in fig. 3.4. The motor arbor is holding the aluminum disc on which polymer coating is applied. The tool shank is supported in multi array orifice air bearing & held in the position by rotating disc. The polymer coated disc & tool shank are in continuous contact with each other. Porous bearings are used only for small loads (i.e. up to 4 to 4.5N) [10]. & Multi array orifice air bearings are used for loads up to 300N [5].

The reason of using aluminum disc is, it has lower density & good machinability, which reduces centrifugal forces & allows accurate machining of disc respectively to reduce rotating imbalance [14].

If the aluminum disc is directly attached with shank two probable problems may arise. One is, less coefficient of friction between disc & tool shank & other is, generation of noise due to direct metal to metal contact. Thus, to overcome stated problems polymer coating is made on aluminum disc. Polymer has good coefficient of friction with carbide & has cushioning property which can transmit motion without generating noise.

The tool is held in air bearing due to radial inward force Rn as shown in Fig. 3.4. whose value is 25 N [10]. When driving disc is rotated, the shank driving force Ft rotates the tool shank. & its value is given by [17]:

$$F_t = \mu R_n \quad \ldots\ldots 3.1$$

Where,

F_t = Tangential driving force in N

R_n = Radial force acting from disc to shank in N

μ = Coeficient of friction

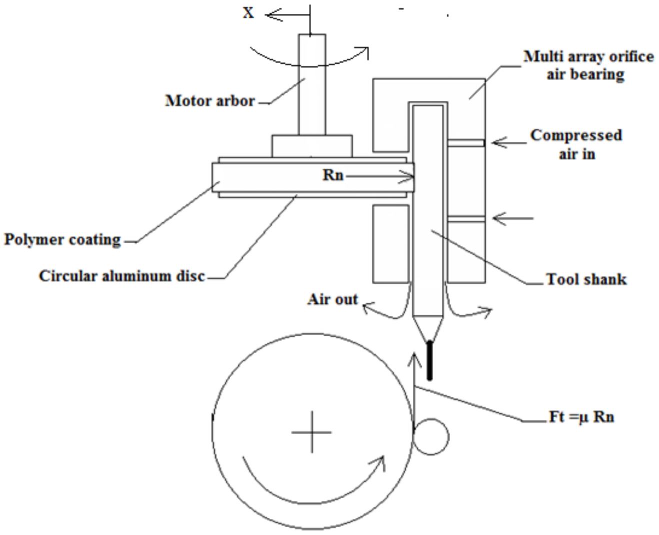

Fig. 3.4 Force diagram of friction disc and tool assembly.

The provision of taking disc away from the tool in X direction as shown in Fig.3.4 is given for replacing the tool. By this arrangement the value of force R_n can be manipulated.

In conventional machines, cutting forces, holding force of collets & driving force of spindle acts on tool shank. But in present case in addition to these all forces Rn is also acting on tool shank. For this reason the design of tool shank is necessary.

Design of spindle includes design of tool shank, Design of drive & Design of bearing.

Designing of tool shank includes, either finding out diameter of tool shank or selecting the standard shank diameter from manufacturer’s catalog & checking induced stresses in it. Then comparing that induced stresses with permissible stress value of tool material. From these two methods, attempt is made to calculate stress generated in tool material whose tool shank diameter is selected from catalog.

‘GUHRING’ tool manufacturing company, USA has high performance solid carbide tools. From the catalog, the standard end mill dimensions are obtained, they are as follows.

Shank diameter = d_2 = 1/8” = 3.175 mm
Tool diameter = d_1 = 1/ 16” = 1.587 mm
Over all length = O.A.L. = 1 ½” = 38.1 mm
Length of cutter = L.O.C. = 3/16” = 4.76 mm

The dimensions are as shown in fig.3.5.

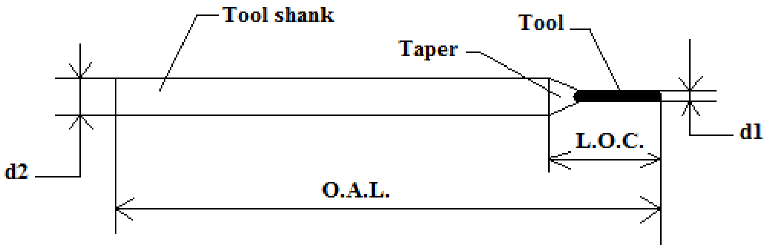

Fig.3.5 End milling cutter

It consists of shank, taper & the actual cutting tool. The cutting tool is two or four flute end mill cutter. This design is necessary for micro end mills to provide tool holding with shank & to keep length to diameter ratio small in fluted region [3]. The tapered design reduces stress concentration & chances of failure.

Before designing the shank for its diameter, the tool in fluted region must be checked for equivalent twisting & bending moment. Because, the tool is considered as cantilever beam loaded at the end. For that design is to be divided in to two parts. One is, checking of tool for equivalent twisting & bending moment for induced shear stress & other is, design of tool shank supported in bearing for its diameter.

End milling is used for producing slots in work piece. There are two cases of milling the slot. First is, the straight slot in which, the cutting force acts only in one co ordinate. Second is the curved slot, in which cutting forces acts in two co ordinates as shown in fig.3.6. For the design purpose the curved path is considered in which cutting forces acts in two co ordinates.

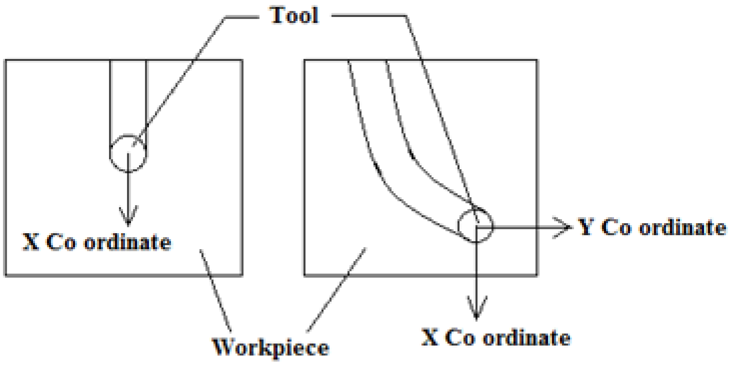

Fig. 3.6 Co ordinates of cutting forces

As discussed above, considering 1.58mm diameter tool is used for the slot cutting. For this tool, cutting forces acting in X & Y co ordinates are 7N & 3N respectively [2]. These values are for spindle speed of 13,000 rpm. But, as the cutting forces in milling do increases significantly with respect to cutting speed, these values can be used for any cutting speed but for 1 mm diameter cutter [10] (in this case the cutter diameter is 1.58mm. as both values are closer, same values of forces of 1mm diameter cutter can be considered for1.58mm cutter.).

Consider fig. 3.4. In this, the driving force F_t is to be calculated.

From equation 3.1

$$F_t = \mu R_n$$

Assuming $\mu = 0.25$

$R_n = 25N$ [10].

$$F_t = 0.25 \times 25 = 6.25 \text{ N}$$

……3.2

This force F_t will create torsion on tool shank. So, torque transmitted to shank is given by:

$$T = F_t \times r$$

……3.3

T = Torque in N mm

r = Tool shank radius in mm = 1.58 mm (i.e. Shank diameter = 1/8") [10, 19].

Substituting above values in equation 3.3 we get,

$T = F_t \times r_{tool} = 6.25 \times 1.58 = 9.87$ N mm. = 9.87 × 10^-3 N m.

……3.4

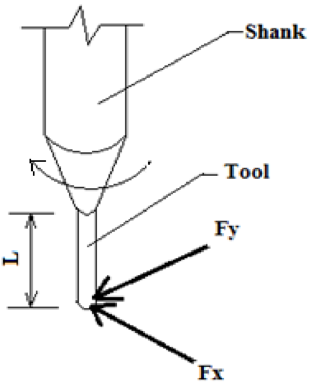

Fig. 3.7 Tool loaded in two co ordinates

Where,

F_x = Force acting in X co ordinate in N = 7 N

F_y = Force acting in Y co ordinate in N = 3 N

L = Length of cutter in mm = 4.76mm (i.e. 3/16") [19]

Considering tool (i.e. length of cutter as shown in Fig. 3.7) as cantilever beam fixed at one end as shown in Fig. 3.8 & loaded by Fx & Fy.

Resolving forces in X direction as shown in Fig 3.8.

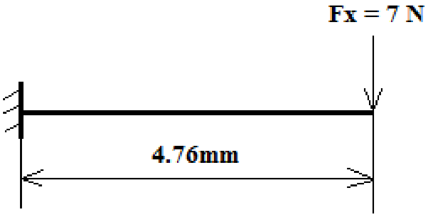

Fig. 3.8 Forces resolved in X co ordinate

Bending moment @ fixed end i.e. Mx

$$Mx = 7 \times 4.76 = 33.32 \text{ N mm.}$$

…… 3.5

Resolving forces in X direction as shown in Fig 3.9

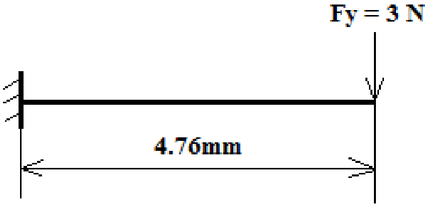

Fig. 3.9 Forces resolved in Y co ordinate

Bending moment @ fixed end i.e. My

$$My = 3 \times 4.76 = 14.28 \text{ N mm} \qquad \text{…….. 3.6}$$

And torque transmitted to tool i.e. T = 9.87 N mm …….. From eq. 3.4

Considering the fluted tool as cylinder, the maximum allowable shear stress is given by:

$$\tau_{max} = \frac{16}{\pi\, d^3}\sqrt{M^2 + T^2} \qquad \text{…… 3.7}$$

Where,

τ_{max} = maximum allowable shear stress of tool material = 95 N/mm^2 [13, 17] (The tool material is Carbide) [19]

d = Diameter of tool in mm = 1.58mm [10]

M = Maximum bending moment in N mm

T = Torque transmitted to tool in N mm

The maximum bending moment from Mx & My is Mx i.e. 33.32 N mm ……..From eq. 3.5

Substituting all values in equation 3.7 we get,

$$\tau_{max} = \frac{16}{\pi\, 1.58^3}\sqrt{33.32^2 + 9.87^2} \qquad \text{……3.8.}$$

From eq. 3.8 τ_{max} is calculated.

$$\tau_{max} = 44.87 \text{ N/mm}^2$$

The induced shear stress is less than permissible value (i.e. 95 N/mm^2) [13, 17] hence design is safe. As the fluted tool is safe for the forces in X & Y co ordinates, the portion of tool is considered as tool shank for designing purpose. Assumption is made that, the tool shank has uniform cross section (i.e. circular) throughout the length, as shown in Fig. 3.10. The dashed lines around the tool in Fig.3.10 represents that the tool is considered as tool shank for designing purpose.

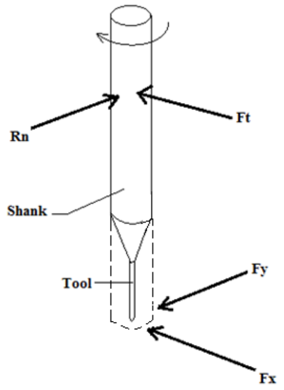

Fig.3.10 Tool shank with all the forces acting on it

The tool Shank is to be supported in air journal bearing as shown in Fig.3.4. The total length of shank is 1.5'' i.e. 38.1 mm. From this total length, leaving 8.1 mm length of shank for installation & removal of tool from bearing the 30 mm length of shank is supported by air bearing [6, 10] as shown in Fig. 3.11.

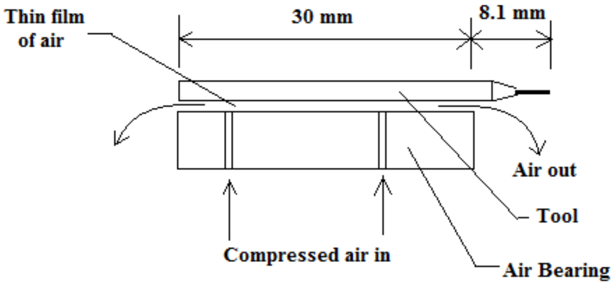

Fig.3.11 Tool supported in air bearing

Once the shank is loaded in bearing the condition will be same as shown in Fig. 3.11. the thin film of compressed air is present in between shank & bearing surface, which avoids direct contact of shank & bearing surface. But, for design calculations the shank is considered as simply supported overhang beam as shown in Fig.3.12.

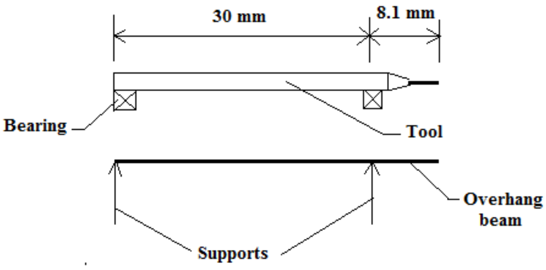

Fig.3.12.Shank considered as simply supported overhang beam

There are four forces acting on tool shank as shown in Fig.3.10. Resolving these forces along X co ordinates. We get forces acting in X co ordinates as shown in Fig.3.13.

The point C is the point where the rotating disc is in contact with tool shank. The contact point C is located 15mm from one end of bearing or in other words, at the center of beam length. Because, only this condition gives maximum bending moment induced in beam. If the beam is safe for this condition then beam will be safe for all other conditions.

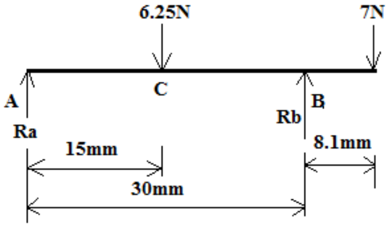

Fig.3.13 Forces resolved in X co ordinate

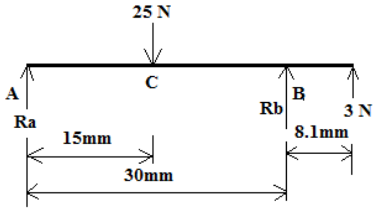

Fig.3.14 Forces resolved in Y co ordinate

By considering this force diagram the maximum bending moment is calculated & by using Equation 3.7 τ_{max} is calculated for selected shank diameter. The calculated value of stress is less than permissible stress value hence design is safe. And shank diameter 3.175mm is considered while doing analysis.

3.2 Geometric modeling of parts of micro milling spindle

As per the calculated dimensions of tool shank, air bearing, friction disc the solid models are prepared in CATIA as shown in Fig.3.18.

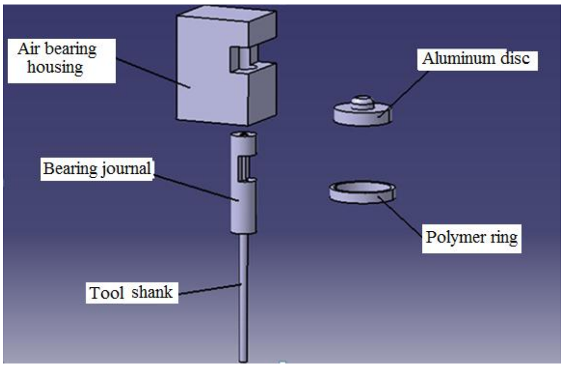

Fig. 3.18 Exploded view of micro milling spindle

The dimensions of each part are shown in following figures & description of the same is given accordingly.

IV. Results & Discussions

Results of simulation of tool shank are obtained from ANSYS. Effect of design parameters is analyzed. Design parameters considered were Modulus of elasticity, stiffness of air bearing, Shank length, Shank diameter, and RPM of shank.

The analysis of tool shank supported in air bearing & Friction wheel is analyzed in ANSYS as shown in fig.4.1.

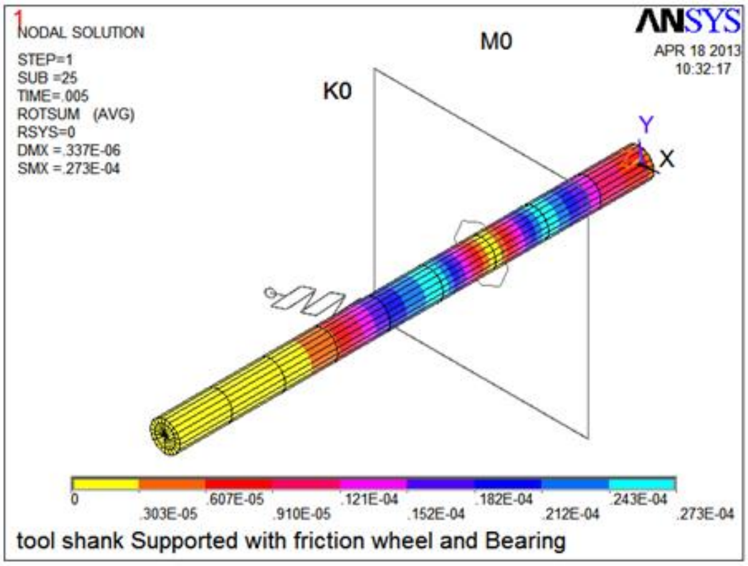

Fig.4.1 Tool shank supported in air bearing & Friction wheel

Fig.4.1 shows tool shank of length 0.0381m & dia 0.0032m meshed with beam 188 element. The spring element shown on back side of tool shank is combi 32 element. The beam element is used for shank. Because, the tool shank in air bearing can be considered as a beam resting on number of springs. And the stiffness of all springs together called composite stiffness is given to single spring as shown in fig.4.1. The square with hole at center shows that the tool shank is supported by the friction disc on other side of composite spring element. In this way the tool shank, air bearing and friction disc are modeled.

Here effect of variation in stiffness of air bearing on run out of tool shank is to be checked at 5000 rad/sec. for varying stiffness of air bearing air flow and air pressure is to be varied. This is done in ANSYS by directly varying the stiffness of spring element. In addition to this, effect of variation in other parameters is also studied by varying that parameter with other parameters constant. The results obtained by simulation are plotted on graphs and discussed below.

4.1 Results obtained from simulation

Number of simulation run has been carried out and effect of varying the parameter on run out is plotted on scatter plot as discussed below.

4.1.1 Effect of varying young's modulus on run out

Young's modulus (EX) is tool shank material property and effect of varying this property on run out of tool shank is shown in fig.4.2.

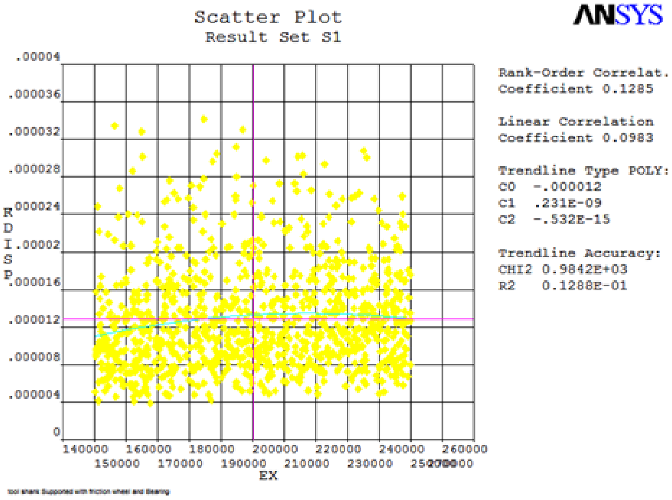

Fig.4.2 scatter plot of Young's modulus Vs run out

The yellow dot on the plot indicates result of single simulation and green line indicates curve fitted of data obtained from simulation. This curve indicates second degree polynomial.

While simulating the range of young's modulus is kept form 1.4×10^11 N/m^2 to 2.6×10^11 N/m^2. For this range the maximum value of run out obtained is 0.000014m and minimum value obtained is 0.000010m. When the EX is 2.2×10^11 N/m^2 the value of run out is maximum i.e. 0.000014m.The graph shows that, once the young's modulus reaches the value of 2×10^11 N/m^2 then graph is sloping down ahead. This means, reduction in run out. If the value of young's modulus is increased, run out goes on decreasing. Hence carbide tool with young's modulus of 6.8×10^11 N/m^2 gives less run out of spindle.

4.1.2 Effect of varying Diameter of tool shank on run out

While simulating the range of Diameter is kept form0.001m to 0.0025m. For this range the maximum value of run out obtained is 0.00002m and minimum value obtained is 0.000008m. When the Diameter is 0.001m the value of run out is maximum i.e. 0.00002m. The plot is as shown in fig.4.3. It shows that as the diameter of tool shank increases run out decreases. This is because it gets maximum bearing area for support. When value of diameter reaches to 0.002125m after that slope of curve goes on decreasing. It implies that, the tool shank diameter more than 0.0025m gives less run out. Hence selected tool shank diameter fulfills the requirement.

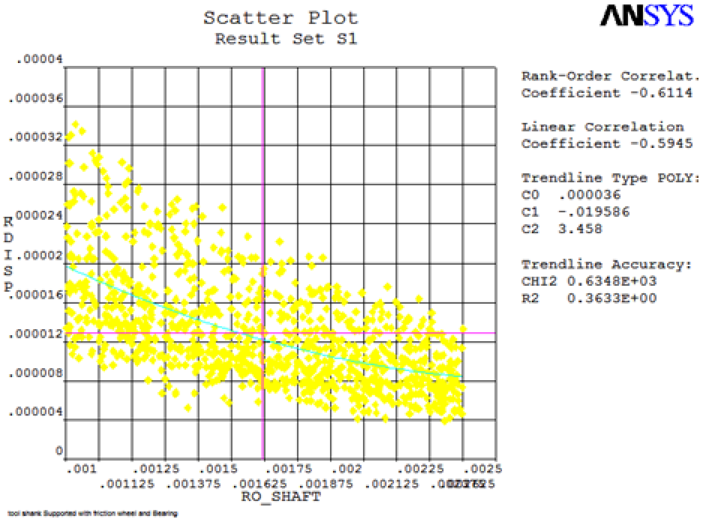

Fig.4.3 Scatter plot of Diameter of tool shank Vs Run out

4.1.3 Effect of varying speed on run out

While simulating the range of speed is kept form 1600 rad/sec to9600rad/sec. For this range the maximum value of run out obtained is 0.00002m and minimum value obtained is 0.00001m. When the speed is 9600 rad/sec the value of run out is maximum i.e. 0.00002m. The plot is as shown in fig.4.4.

The speed range where run out is minimum is 4000 rad/sec to 4800 rad/sec. within this region the run out is 0.00001m.

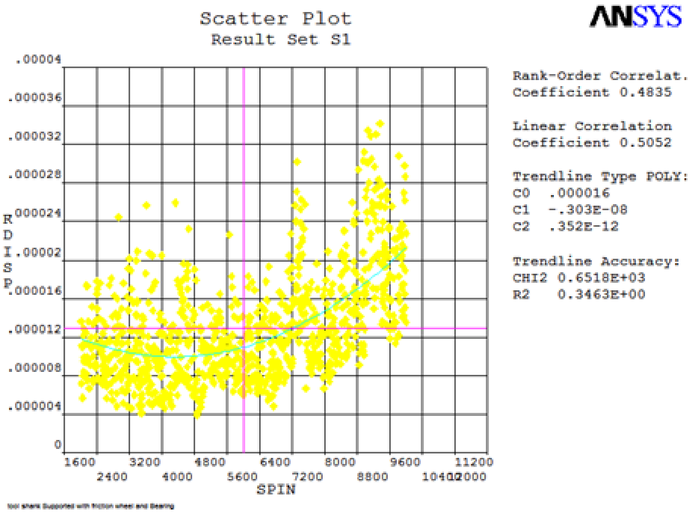

Fig.4.4 Scatter plot of speed of tool shank Vs Run out

4.1.4 Effect of varying length of tool shank on run out

While simulating the range of length is kept form0.03m to 0.05m. For this range the maximum value of run out obtained is 0.000016m and minimum value obtained is 0.000011m. When the length is 0.03m the value of run out is maximum i.e. 0.000016m. The plot is as shown in fig.4.5.

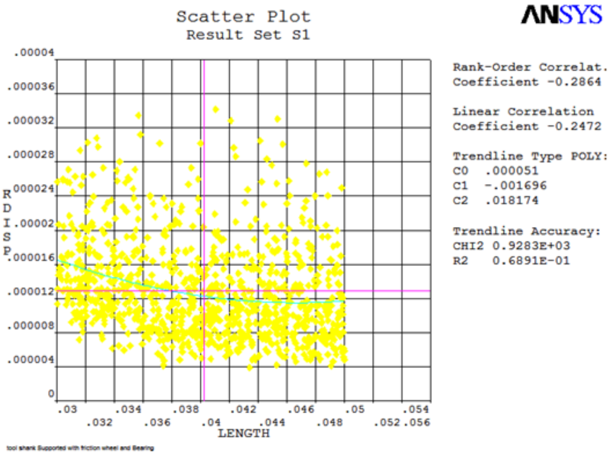

Fig.4.5 Scatter plot of length of tool shank Vs Run out

4.1.5 Effect of varying Stiffness of air bearing on run out

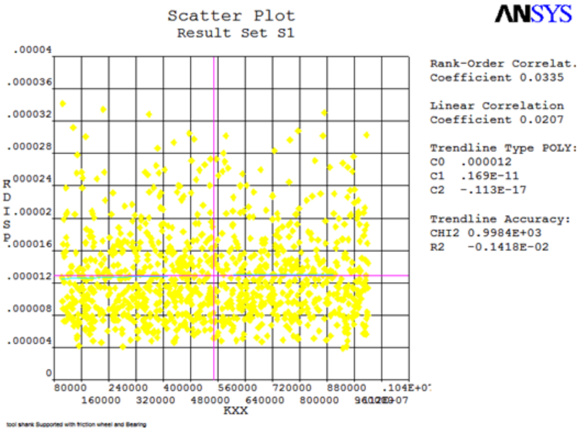

Fig.4.6 Scatter plot of stiffness of air bearing Vs Run out

While simulating the range of stiffness is kept form 8×10^4 N/m to 8×10^5 N/m. For this range the maximum value of run out obtained is 0.000013m and minimum value obtained is 0.000012m. When the stiffness is 8×10^5 N/m the value of run out is maximum i.e. 0.000013m. The plot is as shown in fig.4.6.

4.2 Run out values obtained from simulation

When toll shank is rotated at 5000 rad/sec it shows different values of run out at different sections of tool shank as shown in fig.4.1 and discussed below.

The yellow color indicates minimum value of run out and sky blue color indicates maximum value of run out. The run out is minimum at tool tip and a point where the friction disc is attached to the tool shank. At that point the tool shank is held between air bearing and friction disc, which reduces its radial displacement. The run out is maximum at the points where the tool shank is just supported by air bearing. The maximum value of run out obtained is .273×10^-4 m.

The table.4.1 Shows Comparison of Results obtained from analysis & experimental results from literature for the purpose of validation.

Table.4.1 Comparison of Results obtained from analysis & experimental results from literature

Sr. no.	Parameter	Range of parameter	Maximum run out obtained from analysis	Maximum run out obtained from literature
1.	Young’s modulus	1.4×10^{11} to 2.6×10^{11} N/m^2.	14µm	8µm[4], 12µm[5, 16], 100µm[10].
2.	Diameter of tool	0.001 to 0.0025m.	20 µm	
3.	Speed of spindle	1600 to 9600 rad/sec.	20µm	
4.	Length of tool shank.	0.03m to 0.05m	16µm	
5.	Stiffness of air bearing	8×10^4 to 8×10^5	13µm	

As the values obtained from simulation & values available in literature are compared as shown in Table. 4.1. The maximum value of run out of spindle from literature is 100µm & maximum run out obtained from analysis, in present case is 20µm. There is big gap exists between these two values because, values from literature are results of actual experimentation. Where, all above parameters shows their combined effect & in present case while varying one parameter other parameters are kept constant.

V. Conclusion

Various design parameters are considered and effect of these parameters on run out of spindle is discussed. Analytical design procedure was adopted for designing tool shank, air bearing and friction disc. The CAD models were prepared as per the designed dimensions and analysis of the design is done in ANSYS by simulation. Effect of varying different parameters on run out of tool shank (i.e. spindle) is studied by doing number of simulations in ANSYS and results are plotted on graphs and discussed. The values of run out obtained from simulation & values obtained from literature are compared for validation of results.

The tool with young’s modulus more than 2.6×10^{11} must be used(the material for tool with young’s modulus 6.8×10^{11} is available as per tool manufacturers catalog i.e. carbide), the tool shank diameter must be kept 3.175mm, spindle speed used must be within the range of 4000 to 4800 rad/sec, the length of tool shank is kept in between 38mm to 50mm & stiffness of air bearing is to be kept within the range of 5.2×10^5 to 7.2×10^5N/m so as to have less run out of spindle.

Scope of work in future:-

- Transient analysis of spindle behavior under varying cutting force can be carried out.
- Similar analysis can be carried out for advanced cutting tool material & work piece material.

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