## ABSTRACT

High speed machining (HSM) is a continuously evolving machining technology which is of significant interest in aerospace, automobile and die and mould industries. High speed machining and ultra high speed machining as it is sometimes called is now commonly used to produce thin-walled, pocketed, contoured, and relatively long, wing and fuselage structural members. With HSM, significant improvement in the metal removal rate has been reported. The other benefits of HSM are increased productivity, reduced costs, better surface finishes, lower residual stress, and less distortion.

There are many interesting research problem in high speed machining. Three areas have been investigated in this work:

i. Developing a transient thermo mechanical model to study the thermal response of the spindle.
ii. The distortion of spindle nose at high speeds of rotation and analysis of its effects.
iii. A theoretical study of the dynamics of high speed milling with particular reference to machining of thin walls.

In order to carry out the investigations cited above, numerical models are developed and validated by conducting experiments.

A detailed analysis of the steady state thermal behavior of the spindle has been carried out by Prabhu Raja [104]. The present study is an extension of his study to develop a transient thermo-mechanical model. An integral rotor spindle system with HSK spindle

nose is considered for study. Four different numerical models have been developed towards carrying out the above studies.

First is a transient thermal model of a high speed integral spindle which aims to predict the transient temperature distribution in the spindle unit under various operating conditions.

Heat generation by AC induction motors used in high speed spindles has been studied both theoretically and experimentally. Heat transfer of oil-air lubricant within the bearing is modeled by a forced convection coefficient which is estimated by applying the rule of mixtures for the properties of oil and air.

The heat generation in the bearing inner and outer raceways can be assumed to be equal, so that one needs to consider only a longitudinal cross-section of the spindle assembly to determine the temperature distribution. Further, the geometry of the spindle assembly is also axisymmetric with respect to the spindle axis. Hence, treating the problem as a two-dimensional one is justified.

The mesh developed in ANSYS 8.0 using axisymmetric quadrilateral elements (Plane 78). The boundary conditions applied are, heat generation at the inner and outer races of the bearings, heat generation at the stator and rotor of the motor, free convection between the housing and atmospheric air, forced convection of oil-air at the ball and races and forced convection of the external coolant.

Based on the model, at 25000 rpm, the total heat generation is estimated to be 2533 W, of which 1887 W is contributed by the motor and 646 W due to bearing friction in free spinning condition. On full load, the total heat loss is 4870 W, the motor and bearing frictional losses being 3500 W and 1370 W respectively. The spindle temperature field analysis is then performed using finite element method. The experimental and numerical model results are found to be in good agreement with each other.

The second model of the work consists of two models namely, transient thermo-mechanical model of the spindle unit and the dynamic model of the spindle nose-tool holder unit. The transient thermo-mechanical model predicts the spindle and nose deformation due to the temperature variations in the spindle unit, where as the dynamic model aims to predict the dynamic characteristics of the spindle nose –tool holder interface. The fourth model is a finite element model which is used to investigate the dynamic response of thin ribbed structures under high speed machining conditions. This model can be employed to study the dynamic behavior of aerospace structures and hence established the stable speed ranges to obtain good surface finish.

A thermal- structural coupled field analysis is undertaken to obtain the thermal deformation. The spindle nose deformation has a significant influence on the machining accuracy. The compatible element of PLANE 78 thermal quadrilateral element in structural analysis is PLANE 83. The nodal temperatures obtained from thermal analysis are used as thermal loads. The rear bearing surfaces in contact with the spindle and housing are constrained in only the radial direction, while the corresponding front bearing surfaces are constrained in both radial and axial directions.

The maximum axial and radial deflections are found to be 38 μm and 18 μm respectively at 25,000 rpm on full load against 11 μm and 5 μm on no load. The axial deflection is primarily due to a temperature gradient of 34 $^{0}$C between the front end bearing closer to the spindle at 122$^{0}$ C and the spindle nose at 88$^{0}$ C, along an axial distance of 70 mm. This is evident by comparing the axial deflection considering the effect of only bearing heat generation, which comes to 35 μm for a corresponding gradient of 32$^{0}$ C. Further, the rotor temperature rise at the middle of the spindle is $32^0$ C less than the front bearing temperature and contributes to a lesser extent of the total axial deflection.

The thermo-mechanical model developed in this work can be effectively used for ensuring the safe operation of spindle bearings and minimizing the spindle thermal deformation and hence improve machining accuracy.

The geometry of the spindle nose has a profound influence in high speed machining. The various aspects that influence the spindle performance like radial deflection of the spindle nose, concentricity and balance are considered in this work. A spindle provides drive to either the work piece or the tool depending upon the type of machine tool. The accuracy with which a spindle runs is affected by the elastic deformation of the spindle, its bearing, housing and other components of the arrangement. The stiffness of the bearing overhang and the spindle diameter have considerable influence on the overall stiffness of the spindle system. The industry uses several types of tapers to connect cutting tools to spindles.

The need for adapting machine tool spindles to the requirements of high speed operation has led to the development of many innovative spindle nose designs including HSK. Since the increase in spindle speeds is likely to be a continuous process, it was felt that a study could be initiated to make a quantitative estimate of structural deformation and thermal growth of machine tool spindle noses at high speeds. Since these could be determined using finite element approach within reasonable limits of error, it was decided to carry out a finite element analysis. Structural analysis was carried out for BT and HSK configurations. Since the spindle is axisymmetric, a two-dimensional finite element model of the spindle nose is sufficient to carryout the analysis. The quadrilateral element PLANE 82 is chosen for analysis. The mesh consists of 588 elements and 655 nodes.

The analysis is run for various speeds ranging from 5,000 rpm to 60,000 rpm. The analysis is performed on BT 40 spindle nose as well as HSK spindle nose to make a comparison between the two spindle nose configurations. The radial deformation of the spindle nose is obtained for various speeds ranging from 5,000 rpm to 60,000 rpm. As the rotational speed of spindle increases from 5,000 rpm to 60,000 rpm, the radial deformation of BT40 spindle nose increases from 0.22 micrometer to 31.912 micrometer while it ranges from 0.054 micrometer to 7.77 micrometer for HSK spindle nose. In high speed operations, the spindle growth is a definite disadvantage, since the growth in the spindle nose causes the tool holder to be pulled by the pull stud or other mechanisms. The displacement of the tool holder in the axial direction causes the cutting tool to offset from the workpiece surface. The contact between the cutting tool and workpiece becomes less when the speed increases, which leads to changes in the surface finish obtained by the cutting tool on the workpiece. The more the change in the offset of the cutting tool, rougher will be the surface finish obtained on the workpiece.

The maximum value of translation along X-axis for BT40 is 0.886 micrometer and that for HSK is 0.216 micrometer. Analysis of BT40 nose shows that the translation along X-axis is more at the end of the spindle nose due to the longer taper length when compared to HSK, which shows almost same value of translation along X-axis with respect to the taper length.

In the HSK holder, the results show that the contact between the spindle nose and tool holder is maintained along the taper length at 10000 rpm. The HSK tool holder design, which features a short and hollow taper addresses this problem with two features. One is a clamp that pushes on the tool holder from the inside. Centrifugal force at high speeds actually helps this clamping. The other feature is contact at two faces along the taper, and also along the spindle face. Contact between the mating parts helps in producing the accurate component at high speed. Holding power of tool holder is reduced in the case of BT40 at 10000 rpm when compared to HSK tool holder. Balance is another important factor which affects the accuracy of the machined component.

Because of the high speeds, there are centrifugal effects both on the spindle taper and the tool taper. The spindle expands more than the tool holder and axially displaces itself resulting in reduced contact area and therefore the frictionally engaged transmission of torque reduces. Furthermore, it is obvious that the centering of the tool is no longer guaranteed. Analysis of radial deflection of the spindle nose and the mating tool holder with different tapers shows that for high speed operations, the HSK can give the satisfactory performance. The retention of fit that is obtained in HSK tool holder is the best approach to the spindle nose design for high speed operation. It is therefore conclusively established that the HSK tool holder provides good retention of fit on both the spindle face and spindle taper over a range of speeds.

A neural network model is developed to determine the transient thermal deformations in the spindle nose of a high speed integral spindle. The thermal deformations under transient conditions are predicted for different cooling techniques with the help of neural network. The comparison of axial deformations of different cooling techniques by FEM and ANN is done. It is found that the network can predict the transient deformation with good accuracy

Thin walled structures like bulk heads and isogrid shells are the most common construction elements in aerospace products. These structures are subjected to a variety of large dynamic excitations especially during high speed milling operation. Increasing trend within the aviation industry to benefit from the substantial mass savings together with high structural integrity requires the structures to be light and stiffening ribs to be thinner.

The periodic chip discontinuity inherent with the milling chip formation and associated changing geometry of the cutter lead to cyclic conditions of force. Such varying forces produce vibrations leading to variation of cutting speed with lesser tool life. The varying radial and axial forces may also have a damaging effect on surface finish.

The cutting force, when two flute end mill is used, is dynamic in nature. This will induce vibration in the machine tool- tool- work piece-fixture system. In the present work, only the vibration of the work piece is considered as it is dynamically the weakest. Modal analysis was carried out to determine the vibration characteristics i.e. natural frequency and mode shapes of structure. These are the important parameters in the design of structure for dynamic loading conditions.

Harmonic analysis was then carried out to predict the sustained dynamic behavior to verify whether the structures will successfully overcome the resonance, and other effects of forced vibrations. The mode super position method is used which sums factored mode shapes from a modal analysis to calculate structure response. This method is faster and allows solution to be clustered about the structure's natural frequencies and also accepts modal damping. The maximum deflection at the tool point when the component is machined at 6000 rpm is 16 micrometers, whereas at 30,000 rpm, the deflection is 1 micrometer .

The results obtained in the tests carried out in these three structures are discussed and it was observed that for frequencies higher than certain values, the structures behave in an extremely stiff manner. This means that thin ribs will not undergo any deformation while cutting and thereby it is possible to realize accurate ribs. The investigation reveals that high speed milling is then particularly suitable for machining aerospace structures with thin ribs.

Loss of machining accuracy is a major problem in high speed spindles due to the geometry of the spindle nose and its thermal expansion. In high speed operations, the spindle growth is a definite disadvantage, since the difference in the growth in the spindle nose and tool holder causes reduction in the contacts rigidity between tool holder and spindle nose. The displacement of the tool holder in the axial direction causes the cutting tool to offset from the work piece surface. The contact between the tool holder and the spindle bore becomes less as the speed increases, resulting in geometric inaccuracies and deterioration in surface finish of the work piece.

Realizing thin walls is a critical machining task. A usual problem in the end milling of aluminum structures for aerospace applications is that of maintaining good surface finish on either side of thin ribs, which tends to deflect under cutter pressure. If machining is done at conventional speeds, the cutting force tends to deflect thin ribs so that it is not possible to achieve smaller thickness with dimensional accuracy. The distortion may place a constraint on the achievable thickness of ribs at the desired surface quality. In such a situation, high speed machining may be resorted to in order to overcome the above difficulty.

Under high speed machining conditions, the dynamic response of the structure has important bearing on the stability of the cutting process and needs to be investigated. In this context, it is deemed essential to carry out investigations pertaining to the thermal and dynamic behavior of high speed spindles under various operating conditions with a view of improving the performance. Also, it is necessary to make studies on the dynamic response of thin walled structures during high speed machining for predicting the stable frequency range and to achieve the minimum rib deflection. These investigations are considered imperative in order to achieve the best results in high speed machining.

It is believed that the aerospace industries concerned with machining of thin walled structures and machine tool designers who would continuously want to push up the speed envelope to increase machining productivity will find the methodology and the findings proposed in this work useful.