Study of thermal behaviour in a machine tool using ansys

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ABSTRACT

Smart manufacturing plays a vital role in modern industry. This involves a collection and analysis of data from the machine tool. Also, it requires to study the behaviour of the machine tool. Since the thermal behaviour is critical, machine tool thermal distortion accounts to 60-70% of machining errors, due to which precision and accuracy will affect. The major factor is the thermo-mechanical deformation. Hence, there is a necessity to study the thermal behaviour of the machine tool to reduce thermal errors which results in better machining accuracy. The major thermal sources of the machine tool are internal and external heat sources from spindle and axis movements. In order to study & analyse the influence of thermal sources on the machine tool, this paper focuses on the thermal error modelling approach using FEM (Finite Element Model) analysis. SOLIDWORKS 2016 & ANSYS Workbench 18.1 is used for modelling and to analyse the thermal behaviour mapping.

1. Introduction

1.1 Background and motivation

The main thermal sources in a machine tool, are from the motor, rotation of bearings and the environment temperature which cause thermo-mechanical deformation in the assembly and leads to the machine thermal error, which will eventually affect the precision and accuracy of the machine which also plays a major role in industry 4.0. These thermal errors of spindle consist of radial and axial thermal growth that are time dependant non-linear.

The friction occurs from contact parts, corresponding intensity, thermal expansion coefficient, thermal conductivity and the machine configuration creates complex thermal behaviour in the machine tools. Many kinds of research have verified that the thermal error accounts to 60–70% of the total errors of a machine tool. [1] [2] the Computer Numerical Control (CNC) has two characteristics such as rotation of spindle motor during the operation and the axis motor stroke. These two-play vital roles in machine thermal error and establishes as a key affecting factor on the accuracy of the machine. [3]

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Position dependent thermal deformations play a major role in thermo-mechanical error. Depend on the clamping position on the table, the temperature distribution over the table varies. Deformation of the clamping table increases when the ball screw is placed near the heat source. When the ball screw is away from the heat source, temperature distribution over the table will reduce therefore deformation also reduces.[4]

Geometric errors are less complicated than thermal errors because the temperature distribution on a machine will change depending on the complexity of machine structure, process temperature and varying environmental conditions. The time-varying thermal error depends on the heat generation in the machine on running condition that eventually leads to thermal expansion of the machine.[5] The periodic fluctuation of temperature in a machine due to environmental changes and external heat source will be lower as the internal heat source fluctuates rapidly to reach the equilibrium condition.[6]

This paper enables to understand thermal deformations, thermal error, and thermal behaviour of the machine. And also, the relation between the temperature and deformation of the machine part. Varying temperature deformation can be calculated from the data collected, that can also be used in smart manufacturing. As lead screw plays an important role in the power transmission unit in a linear scale, this paper analyses the x-axis bed on the Vertical Machine Centre (VMC). which comprises of with AC servo axis motor, ball screw, lead screw with duplex back to back thrust bearings at both ends for rigid support to withstand axial load and radial load, and clamping table over which the machine vice is attached. Depend on the speed of the axis motor, the heat-producing from the motor and the bearing support on both the ends will increase. [7] This generated heat develops a thermal expansion in the lead screw so that the clamping table mounted on it gets affected with position drift and it is pulled towards either side of the machine co-ordinate.[8]

1.2 Experimental setup

In this paper, the lead screw of Vertical Machining Centre (VMC) is considered for the evaluation of thermal error and temperature distribution. Alone with the lead screw, ac servo motor (x-axis), flexible coupling (torsional stiff coupling), axis bed, all the axes screw (drive ends) have common mounting details with a small difference. This experiment concentrates on longitudinal axis in which the drive end of the ball screw is supported with duplex precision angular contact bearing. In case of cross and vertical axis, the drive end is supported with a set of quadruplex precision angular contact bearing. In the case of the longitudinal axis, it maintains a back to back bearing configuration for the rigid support of the machine. All these axes (longitudinal, cross, vertical) are driven by independent A.C. servo motor.

2. Thermal Model

Simplified axis model was drawn by referring the geometrical dimension of a Vertical Machine Centre and the technical data such as the axis arrangement, materials, properties and standards of machine parts from the machine maintenance manual which gives the exact material concentration to each part of the machine while carrying out the thermal analysis in ANSYS 18.1. Fig 1 shows the schematic diagram of x-axis bed in Vertical Machine Centre (VMC).

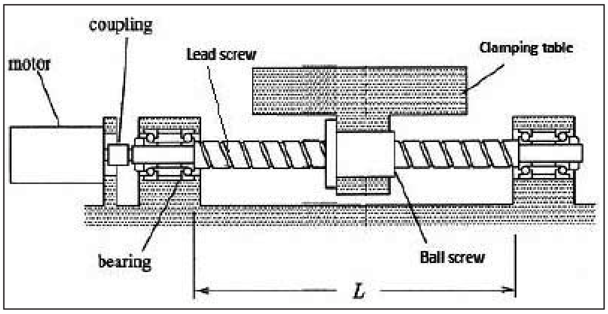

Fig. 1. Schematic of feed drive (x-axis) VMC machine.

Table 1
Parameters related to machine.

Item	Specification
Clamping table (L x W)	860 x 460 mm
Max load	500 kg
X-axis stroke	710mm
Y-axis stroke	450mm
Z-axis stroke	450mm
X-axis Motor	1.2KW
Y-axis Motor	1.2KW
Z-axis Motor	2KW
Main motor	5.5-7.5 kW
Overall size L x W x H	3000 x 3600 x 3000 mm
Lead screw diameter	32 mm
Pitch	10 mm
Lead screw length	1100mm
X-axis bed length	1400mm
Maximum speed	2000r/min

Table 1 gives a detailed specification of the machine in which thermal analysis was carried out. To perform thermal analysis and static structural analysis in ANSYS, the boundary and the thermal conditions need to be confirmed first before selecting the mesh size and meshing method.

Figure 2 shows the FEM model of axis bed with mesh size 12mm, patch conforming method, tetrahedrons method with elements 134752 and

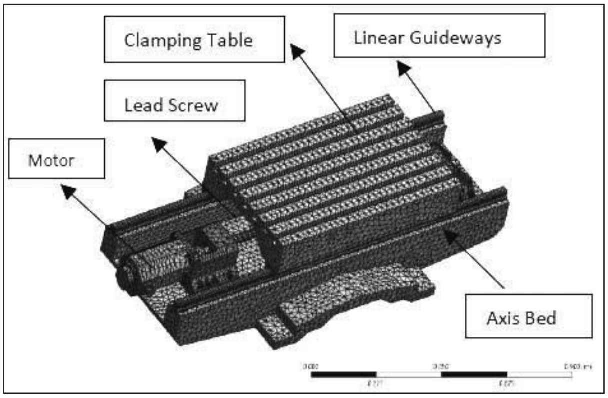

Fig. 2. The FEM model of the feed drive (x-axis) bed.

Table 2
Thermophysical properties of lead screw material.

Material	SS304
Density	7750 Kg m^3
Thermal Expansion Coefficient	1.7E-05 µm/m/^{0}c
Poisson's ratio	0.31
Thermal conductivity	15.1 W/m ^{0}c
Specific heat	480 j /kg ^{0}c
Tensile yield strength	207 Mpa

nodes 239702. Geometry includes 20 parts each having different material properties. lead screw material used in this experiment is SS304 but, many other machines uses AISI4150H both having entirely diverse thermo-mechanical properties. Types of contact used in ANSYS are Bonded contact, No Separation Frictionless contact, Rough contact, and other 32 Frictional contacts are considered in this geometry.

2.1 Static structural analysis of axis bed

Firstly, the static structural analysis with the varying thermal condition is carried out. The initial temperature of the machine is considered to be ambient, once the machine is started running, heat is generated and comparatively more heat is generated in the surroundings of the motor. Due to which the shaft starts to transfers the heat to a coupling which is then transferred to the lead screw. The coefficient of friction on the contacts and the thermal condition which is applied only to AC servo motor x-axis and the Following constrains considered for analysis, Cylindrical support is given to both side of the lead screw in order to achieve higher stiffness and displacement accuracy. One end of the lead screw is fixed because of the motor and

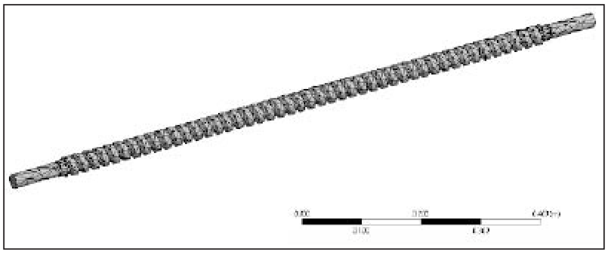

Fig. 3. The FEM model of the lead screw.

coupling arrangement, the other end has back-back angular bearing which allows expanding axially. By performing static structural analysis with the above-discussed constraints, gives an inference for future work and the reduction in the working boundary to be done. Comparing with (X, Y, Z) expansion x-axis shows more thermal error. The most affected part in this x-axis bed due to the material properties and direct contact of heat can be concluded as the Leadscrew.

2.2 Heat generation

Lead screw and clamping table gets affected by Four major heat generation areas such as,

1. Heat engendered by support bearing due to the friction between the ball sand races.
2. Nut and screw shaft.
3. The motor.
4. Guideway.

The heat generated and transferred through conduction method so the temperature distribution throughout the body is different. And when the heat is applied on one side of the lead screw, due to the convention and atmosphere condition heat loss may occur. And in a certain time, it will reach the equilibrium condition having null temperature change.

Also, here time plays an important role so, transient thermal analysis needs to be performed to get temperature distribution axis. [9] When a motor is running for 1-2 hours deformation values varies with time and the error is also time-varying and non-linear thermal error. Due to all the above-mentioned heat generation, positions drift may occur at clamping table so as the change in accuracy.

3. Experimental Works

The main objective of this paper is to study and analyse the thermal behaviour, effect of

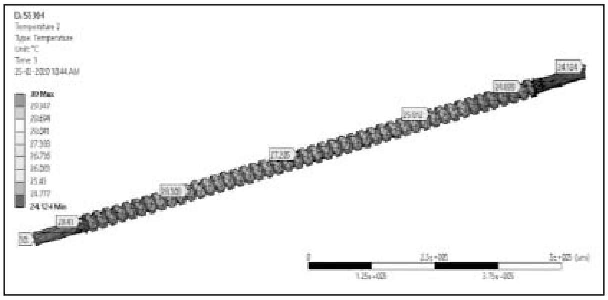

Fig. 4. Temperature distribution on the lead screw.

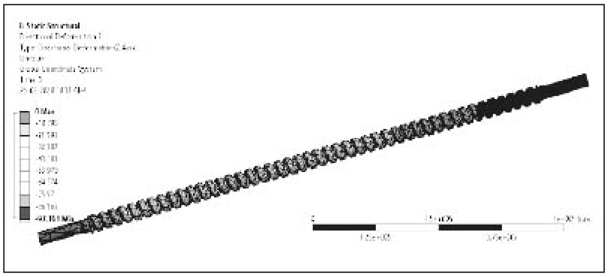

Fig. 5. Thermal deformation in the x-axis.

ambient temperature and other heat sources on a machine element using FEM analysis. The static structural analysis gives a conclusion that most affecting part are lead screw so the paper mainly focuses on lead screw thermal error for which input parameters are thermal condition and constraints. Time-independent thermal error needs to be calculated, so at the first place, the temperature distribution along the lead screw need to be known for which steady-state thermal need to analyse that is linear analysis without considering the time.

The Input thermal data of the motor used for Ansys analysis is noted down manually using a temperature sensor placed on the motor for the whole day. With the existing data of the motor, steady-state was carried out. The thermal deformation of the lead screw at each temperature is to be calculated by multiple system analysis. This will combine steady-state thermal analysis and static structural analysis. By importing the solution of steady-state thermal analysis to static structural analysis then fixing the constraints to one end of the lead screw because that end is coupled with torsional stiff coupling and AC servo axis motor. So, heat is generating at one end and heat is flowing axially from one end to another end. The other end is non-constraints in the axial direction. Figure 4 shows when the motor is with thermal condition 30^0C, the input temperature is 30^0C and ambient temperature 22^0C. The temperature at the other end of the lead screw is 24.124^0C. The temperature at another end attains equilibrium condition.

Table 3
Thermal expansion in x axis ANSYS results.

T1 Input temperature (^{0}C)	T2(^{0}C)	Deformations in x axis (- direction) (µm)
25	22.797	-36.435
28	23.593	-72.871
30	24.124	-97.161
35	25.452	-157.89
40	26.779	-218.61

4. Results and Discussions

Table 3 shows deformation in x-axis with respect to the input temperature applied at one end of lead screw T_1 from the sensor which is attached at the key points of the T_2 is the temperature generated at other ends of the lead screw by conduction process of the axial heat flow from one end to another. Deformation in x-axis is due to the input temperature.

To validate the analysis, heat transfer equation is used. Table 2 shows the thermophysical properties of lead screw material which is considered here.

The temperature difference across the end is

$$\Delta T = T_1 - T_2$$

For steady-state operation

$$Q_{conduction} = Q_{convection}$$

Rate of heat transfer (Q) is inversely proportional to the surface area of geometry (A), temperature difference(T_1-T_2), length of the material (L)

$$\frac{Q \infty \text{ (Surface area) x Temperature difference}}{\text{length}}$$

$$Q_{conduction} = \frac{(KA(T1-T2)}{L} \qquad (1)$$

$$\frac{dq}{dt} = -\frac{KAd\theta}{L}$$

Heat transfer equation by conduction is equal to Heat transfer equation by convection from one end to the atmosphere in the lead screw. The convection on the surface of the lead screw

Table 4
Results.

	T_2(^{0}C)	Deformation (x-axis)
Calculated	23.849^{0}C	ΔL = 95.8μm
Simulated (ANSYS)	24.124^{0}C	ΔL = - 97.1μm

is neglected. H is a convective heat transfer coefficient, T_{Atm} is environmental temperature.

$$Q_{convection} = HA(T_2 - T_{Atm}) \quad (2)$$

By combining the above two equations Eq. (1) and Eq. (2) T_2 can be found, where K is the thermal conductivity

$$\frac{KA(T1-T2)}{L} = HA(T_2 - T_{Atm}) \quad (3)$$

Therefore, T_1 and T_2 are found, both are the temperature at both ends of lead screw next need to find whole body temperature.

Here, deformation at x-axis where L is the length of the lead screw, α is the thermal expansion coefficient

Change in length (ΔL)

$$\Delta L = \alpha L\Delta T \quad (4)$$

Analytical calculation and the simulated result are comparing for the validation of multiple system analysis performed

Future works focus on transient thermal analysis with respect to time which is time-varying nonlinear unsteady-state thermal analysis.

5. Conclusion

This paper focus on the study of thermal behaviour of machine tool, the thermal expansion of lead screw was examined at different temperature using Finite Element Method (FEM) and study from analysed thermal deviation, hereby conducting the x-axis bed static structural analysis using SOLIDWORKS 2016 and ANSYS 18.1, the attained result conclude that lead screw gets affected more. further analysis carried out on steady-state and static structural for thermal expansion in the x-axis of the lead screw SS304. The thermal errors were calculated and simulated are validating. And these analysed results provide a solution for smart manufacturing technology. In future focussing on transient analysis to improve the simulated result.

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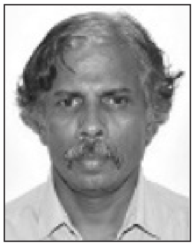

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