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THERMAL BEHAVIOR IN CNC MACHINE-TOOLS

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Abstract: This article describes errors in machine-tools focusing on thermal errors. The internal and external heat sources in machine tools. The basic concepts of heat transfer and an introduction to Finite Element Method FEM applied to heat transfer.

Keywords: *machine-tools, heat sources, heat transfer, manufacturing errors, Finite Element Method*

1. INTRODUCTION

Thermal behaviors in machine tools are from many years the case of study in universities and manufacturing companies. Effects related with thermal deformation in machine tools can influence the accuracy of the manufactured pieces. It lays on how precise are the movements between the machine tool and the workpiece. If the deformations overlap the established tolerances, the workpieces will require more machining process and it will increase the cost of production.

The most relevant part of disturbance in the production systems and production processes are related with the loss of energy, which is transformed in heat energy. Part of this energy will be transferred to the machine-tool and workpiece and the other part to the surroundings. The transfer of energy provokes the thermal deformations in the process.

The machine tool's heat behavior is determined by the output of the heat sources, primarily shown as power losses in the friction nodes and electric motors located within the structure, the increase in the temperature of the machine tool components at certain points, the temperature distribution, the thermal deformations of the load bearing system, and the mutual displacements of the assemblies [1].

2. ERRORS

The deviation of the measured value (assumed) from its true value is called error. There are two kinds of errors:

- Random errors.
- Systematic errors.

Random errors have a relation with the precision of results and are treated statistically. The magnitude of the random error is analyzed from the results of a set of repeated measurements. Systematic errors occur at every measurement in the same way and cannot be analyzed by examining the results.

Theoretically, the measured value $x_{measured}$ from an instrument must be identical to the true value x_{true} [1].

$$X_{true} = X_{measured} + Error \tag{1}$$

2.1. Main errors related with machine tools

Errors in machine tools that are described in this section are studied and analyzed in the field of precision engineering manufacturing due to the importance in the performance of the machine and in the final results in the products created in different kind of machine tools.

Motion errors

Usually a machine-tool, depending on the application can perform movements in 3D space. Three translational movements along the axis x, y, z and three rotational movements pitch, yaw and roll respectively about x, y, z.

Translational errors

Generated by geometric deformations, design or physical properties that can produce the next effects:

- Positioning errors.
- Straightness of each axis in ITS perpendicular axes.
- Abbé error.
- Reversal errors.
- Backlash errors.
- Flatness error.
- Orthogonality error between two axes.
- Friction and stick slip motion errors.
- Parasitic movements.
- Inertia force errors in transient movements (braking/accelerating).

Rotational errors

In spindles and chucks can occur deviation from the datum point. Angular deviation and radial displacements can occur about x, y and z axis.

Associated errors with rotational motion are:

- Out-of-round.
- Eccentricity.
- Radial throw of an axis at a given point.
- Spindle radial deviation.
- Spindle axial deviation.

- Spindle inclination.
- Pitch, roll, yaw angular errors.

Geometric errors

Constitute a large source of inaccuracy, due to design, built-in during assembly, tolerance of components used on the machine.

Thermal errors

Thermal errors of machine tools are one of the main contributors for geometrical inaccuracies of machined workpieces and deformations [1].

Thermal errors account for 70% of the total dimensional and shape errors in machines. This type of errors have either a dynamic or quasistatic behavior. Related with cost, it is more effective to compensate thermal errors rather than using expensive and high-precision components for the machine construction.

3. INTERNAL AND EXTERNAL HEAT SOURCES IN MACHINE TOOLS

Internal heating sources are related with the inner machine components that belong to the part of the machine such as:

- Bearings.
- Linear electric motors.
- Servomotors.
- Belts and chains.
- Hydraulic systems.
- The material used for the construction of different parts of the machine.
- Linear and rotational rail guides.
- Caged ball motion blocks.

External heating sources are related with the environment and the surrounding influences exerted over the machine-tool. These external heating sources are:

- Temperature distribution (vertical/horizontal).
- Temperature fluctuations (day, night, seasons of the year).
- Air conditioning systems inside the workshops.
- Air currents.
- Thermal memory for a previous environment.
- The shop floor environments where the machine is located.
- Meteorological factors.

Temperature controlled environments require high capital investments and running costs. Which are undesirable and impractical in some cases [2].

4. Heat transfer in machine tools

The thermal behavior of a machine tool during its operating condition and the influence on machining accuracy depends on the heat exchange between the machine tool and the environment, the heat transfer within the housings and the load-bearing structure of the machine tool.

Accumulation of large quantities of heat close to intensive heating sources in the machine tool may affect its geometrical accuracy. This means that heat transfer conditions should be rationally shaped during the design. Using a heat model based on FEM and running numerical simulations of the heating up and deformation of the machine tool, one can design optimum heat transfer model by selecting materials with favorable thermal conductivity and creating proper conditions of heat transfer through the joints between the machine tool components and housings, through natural convection or forced convection by the linear or rotary motion elements, and through controlled heat abstraction by cooling overhead places [1].

4.1. Heat transfer modes

Heat transfer studies the energy transport between material bodies due to temperature difference [3]. The three modes of heat transfer are:

- Conduction.
- Convection.
- Radiation.

Conduction occurs due to the exchange of energy from one molecule to another without motion of the molecules, or it can be due to the motion of free electrons. This mode of heat transport depends on the properties of the medium and takes place on solids, liquids and gases.Molecules that are present in liquids and gases can move freely from hot to a cold region. During the motion, the molecules carry energy with them.

The transfer of heat from one region to another due to the macroscopic motion in liquids and gases is called heat transfer by convection. Convection may be free, forced or mixed. Natural or free convection occurs due to a density variation caused by temperature differences. Forced convection occurs when energy is transferred to the fluid by an external force (fans, pumps, blowers, etc.). Mixed convection occur when natural and forced convection are present.

Radiation does not require a material medium for heat transfer to occur. The propagation of energy is carried out by electromagnetic waves. When the electromagnetic waves strike other body surface, one part is reflected, another part is transmitted and the other part is absorbed.

All the materials can emit thermal radiation at all temperatures [2].

4.2. Heat transfer laws

To quantify the energy transferred per unit time is needed to apply rate equations. For heat conduction the heat transfer equation known as the Fourier's equation quantifies the amount of energy transferred per unit time per unit area.

$$q_x = -k\frac{dT}{dx} \tag{2}$$

Where:

- q_x Represents the heat flux in one dimension $({W}/{m^2})$.
- k The thermal conductivity that is a material property of the body $({W}/{mK})$.
- ${dT}/{dx}$ The temperature gradient $({K}/{m})$.

Heat convection follows Newton's law of cooling.

$$q = h(T_w - T_\alpha) \tag{3}$$

Where:

- q Represents the heat flux $({W}/{m^2})$.
- $(T_w - T_\alpha)$ Temperature difference between the surface of a body and the fluid.
- h Heat transfer coefficient $\left({W}/{m^2K}\right)$.

In heat conduction through solids, the heat transfer coefficient appears as a boundary condition in the solution of heat conduction through solids.

Flux that can be emitted by radiation from a black surface is given by the Stefan–Boltzmann Law.

$$q = \sigma({T_w}^4) \tag{4}$$

Where:

- q Represents the radiactive heat flux $\left({W}/{m^2}\right)$.
- σ Stefan–Boltzmann constant $5.669x10^{-8}\left({W}/{m^2K^4}\right)$.
- T_w Surface temperature.

The increase of energy in a system is equal to the difference between the energy transfer by heat to the system and the energy transfer by work done on the surroundings of the system.

$$E = dQ - dW \tag{5}$$

- Q Total heating entering the system.
- W The work done by the surroundings.

The rate of energy transfer is expressed by the equation:

$$\frac{dE}{dt} = \frac{dQ}{dt} - \frac{dW}{dt} \tag{6}$$

5. Finite element method for heat transfer

The finite element method is a numerical tool for determining approximate solutions to a large class of engineering problems. In the finite element method, the actual continuum or body of matter (solid, liquid, or gas), is represented as an arrangement of subdivisions called finite elements.

Elements are interconnected at specified joints. Since the variation of the field (displacement, stress, temperature, velocity, pressure) inside the continuum is not known, assuming that the variation of the field variable inside a finite element can be approximated by a simple function. These functions known as interpolation functions are defined in terms of the values of the field at the joints. By solving the field equations, the nodal values of the field variable will be determined.

FEM has received considerable attention in engineering education and in industry because of its diversity and flexibility. Although it is possible to derive the governing equations and boundary conditions from first principles, it is often difficult to obtain any form of analytical solution due to the fact that either the geometry is irregular or boundary conditions are complex [3].

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