Simulation Approach to Evaluate the Thermal Behavior of A 3-Axis Milling Machine Based on FEM

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***Abstract*—This paper presents a virtual simulation system which is employed in order to evaluate the thermalbehavior of a 3-axis milling machine tool. The thermal behavior of a machine tool is identified in terms of temperature field and thermal deformation. The paper discusses the evaluation aspect of the desired system, determines the heat generation at the major hot spots of the machine, and introduces a case study to evaluate the thermal behavior of a 3-axis milling machine tool based on the FE technique. Obtaining such a reliable model could replace many experimental tests that must otherwise be carried out each time the parameters affecting the thermal behavior are changed.**

Keywords—Machine tools; Thermal behavior; (FEM) Finite element method; Heat generation; Sliding friction; Feed drives.

I. INTRODUCTION

Milling operation is very common in manufacturing. It often represents the last operation, determining the final product quality. The experimental approach to study the thermal behavior of a machine tool is expensive and time consuming, especially when a wide range of parameters are included. Hence, virtual prototyping is needed in order to study the effect of heat generated at the hot spots on the machine tool thermal behavior. The increase in speed of analyses allows for an increased number of concepts to be evaluated and optimized resulting in a higher quality concept while simultaneously reducing the whole product development time and cost significantly.

The thermal performance of a machine tool depends on parameters related to cutting process, such as: cutting speed, feed rate, radial and axial depth of cut, and end mill and work piece characteristics, and other parameters related to the hot spots at the machine structure, such as: guide ways, electric motors, bearings, and screws. Among various mathematical models used for steady state thermal simulation, finite element method (FEM) is proved to be useful and widely used. Introduction to FEM and its basics are represented in details by .

One of the early works that studied the machine tool behavior in general was developed by [1]. As the thermal deformation is considered one of the crucial parameters that affect the product quality, [2] studied the reduction and compensation of thermal errors in machine tools. A foundation and comprehensive information related to the field of virtual machine tool design were presented by [3].. "Temperature field modeling and thermal deformation analysis of turning and milling machine Center" was developed by [4]. This work focused on the sources of heat and the distribution of important hot spots taking into accounts the moving parts. The steady state temperature field and the thermal deformation of saddle have been represented. The heat source in the machine tool has been mainly found in the three guides of the cross bar and the two guides in the machine base. Other work that focused on the heat generated due to the cutting process is developed by [5]and is entitled: "The influence of cutting parameter on heat generation in high-speed milling Inconel 718 under MQL condition". In this work, the authors created a mathematical model that employs the response surface methodology (RSM) based on experimental results. Moreover, the analysis of variance (ANOVA) was applied to check the significant contributing factors affecting the cutting temperature, during the end milling process. The results proved that the parameter of the highest influence is the radial depth of cut followed by the axial depth of cut, while the effect of cutting speed and feed rate were found not significant. Finally, the mathematical model was applied on a certain case to determine the optimum cutting condition at which the cutting temperature is the minimum. On the same context, the heat generation due to friction between guide ways and sliding parts were studied by [6]. The paper is entitled "Effect of thermal deformation on machine tool slide guide motion". The relationship between the coefficient of friction, contact pressure, velocity, and feed rate is determined experimentally at various surface quality levels. The thermal deformation at the guide ways and their effect on the straightness of the vertical and lateral directions are studied. Finally, the table motion during single stroke is represented. Along the same lines, "Simulation of thermal behavior of a CNC machine tool spindle" was developed by[7]. The paper proposes a method for computing the coefficient of convection heat transfer of the spindle surface. Moreover, the temperature field and thermal errors of the spindle are dynamically simulated under the actions of thermal loads using the FEM. Then, according the simulation results, the characteristics of heat flow and thermal deformation within the spindle are analyzed. Finally, the system is verified against experimental results.

In this paper, a system that employs the concept of virtual prototyping is created to provide designers of milling machine tools with useful information, and to facilitate improvement decisions in the early design stage. The system evaluates the thermal behavior of milling machine tool in terms of temperature field and thermal deformation. The system alsointegrates the thermal deformation and the static deformation resulted from cutting loads to determinethetotal deformation of the entire machine.

II. DEFINITION OF THE EVALUATION ASPECT

In order to study the temperature field and thermal deformation of the machine tool and their effect on the entire error generated, several heat sources in the machine tool are studied. The main sources of heat generation of the machine tool are the sliding friction at guide ways, electric motors, rolling friction at bearings, rolling friction between screws and nuts, and the cutting-heat.

To achieve thermal evaluation for the machine tool, the construction of the virtual evaluation system is designed to contain a thermal analysis module to which all data related to the heat generation in the machine tool is transferred, and at which the temperature field and the thermal deformation all over the machine tool are determined. The data entry of the evaluation system contains data related to the heat generation (Q ($W/m^2.C^o$) at the hot spots of the machine tool, and data related to the thermal properties of the material assigned to various elements of the machine tool such as coefficient of thermal conductivity ($W/m.C^o$), specific heat ($J/Kg.\ C^o$), and coefficient of thermal expansion.The FE model used in thermal analysis is represented by the following formula:

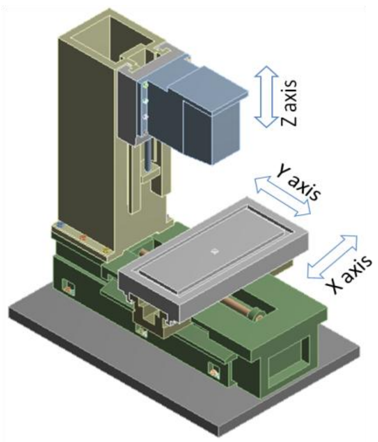
$$[q\ (t)]\ \{T\} = \{Q\ (t)\} \qquad (1)$$

Where (q) represents the thermal resistance of the system which can be constant or varied with temperature (t), {T} is the temperature matrix similar to the displacement matrix in the mechanical modules, and (Q) represent the load which is the heat generation in the thermal studies.Practically, the heat generated at the hot spots grows along the time at which the machine tool start moving to the time it reaches a thermal balance. The study of the transient state of the thermal deformation is not considered in this paper. Furthermore, the TCP deformation generated due to the static load is integrated with that generated from thermal analysis to provide a comprehensive evaluation of the machine tool performance based on the total deformation at the TCP.

III. MODELING OF THE MECHANICAL STRUCTURE

The mechanical structure of a machine tool center can be considered to have the major contribution of its thermal behavior. When the machine tool is exposed to high thermal and static loads, the characteristics of the mechanical structure become crucial. The machine structure mainly consists of the column, bed, table, saddle, and spindle head. The feed drives of the machine including the ball screws are all designed based on approaches developed by[8], while the bolted connections are designed with the guidance of the approach developed by [9]. The machine column is designed according to the considerations and limitations discussed by [10]The CAD model shown in Figure 1(a) is created using any of the commercial CAD software and imported to Ansys® which is the analysis tool package used in this work. Before creating the FE model of the machine tool structure, Small holes, chamfers, fillets and other tiny details areignored to simplify the model so that a high quality mesh can be obtained with minimum computation time[11].

The FE model of the mechanical substructures are generated from their perspective CAD models using tetrahedron elements. The tetrahedron elements are proved to be more suitable than the bricks elements to simulate machine tool structures. Figure 1 (b)shows the FE model of the machine tool mechanical structure. The main characteristic of interest when evaluating a FE model is the mesh size. The fine mesh size leads to converged results, but on the other side, it increases the DOFs which increases the computation cost as well. However, local refinements in mesh size can be specified at critical regions such as TCP and work table using the sphere of influence. To obtain a mesh independent model with the minimum computation time, constitutive iterations are carried out to properly select mesh characteristics in order to achieve convergence of the results to the exact value within an accepted residual error. The h-method in which the mesh size is refined until convergence is employed in this work. This method is preferred for its ease of execution rather than the P-method in which the degree of polynomial used for the shape function is changed until convergence[12].



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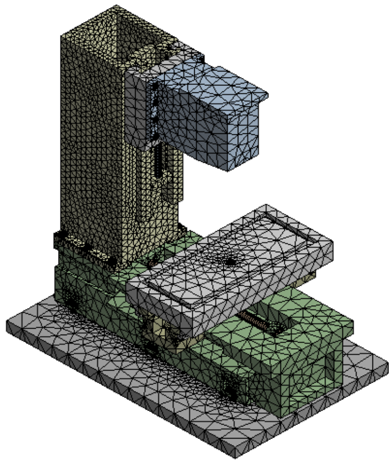


(b)

Figure 1 3D model and FE model of a 3-axis open category milling machine tool.

IV. HEAT GENERATION OF GUIDE WAYS

The guide ways are essential elements of a machine tool that supports the traverse motions necessary for the cutting process. They have great contribution in affecting the static, dynamic, and thermal performance of a machine tool.

The sliding motion occurs at the guide ways is considered one of the main sources of heat in the machine tool[6]. The heat is generated from the friction among the sliding parts. Practically, the friction-heat generation grows when the sliding starts until it reach a steady state. The transient thermal behavior is not considered in this paper. The friction-heat can be represented by the following formula:

$$Q_s = \eta.\mu.F.\upsilon \qquad (2)$$

Where Q_s is the sliding friction heat (W), η is a factor ranges from 0 to 1, μ is the overall coefficient of friction, F is the external load which is the weight of the sliding part or the bolts preload, and υ is the sliding velocity (m/s).

As proved in the above formula, the friction heat generation is directly proportional to the sliding velocity. Hence, the friction heat is usually calculated when the sliding parts move with the maximum feed rate which mainly occurs at the non-cutting intervals. On the other hand, the overall coefficient of friction depends on several terms such as: the contact pressure, the viscosity and the thickness of the lubricant film, the sliding velocity, and the smooth degree of the guide way surface.

To determine the thermal deformation of the guide ways, the overall coefficient of friction is first determined experimentally. The friction-heat Q is then calculated and transferred to the steady state thermal analysis module at which it is assigned to the guide way surfaces in (W/m^2.sec). Moreover, the thermal properties of the studied part (e.g. saddle) are assigned. Finally, the thermal deformation of the sliding parts and guide ways is determined and its reflection on the geometrical error of the final product is studied.

V. HEAT GENERATION OFFEED DRIVE UNITS

Screws and drives are essential parts in a machine tool center that are responsible for the traverse motion of both spindle head and work table. However, they are considered the weakest points from the aspect of dynamic performance especially when the machine tool is exposed to low frequency dynamic loads[13]. As shown in Figure 2, the feeding system mainly consists of the feed drive, the screw, and the supporting bearings.The heat generated at each component is discussed as follows:

A. Heat generation of electric motor

The main source of heat in the electric motor is due to the copper loss[4]. The heat generated can be obtained by the following formula:

$$Q_m = (1-\eta_m).735.P.\eta_h \qquad (3)$$

Where Q_m is the heat generation at electric motor (W), η_m is the motor efficiency, P is the motor horse power, and η_h is the heat loss percentage.

B. Heat generation of bearings

The heat generation in the bearing is mainly resulted from the total friction moment (M_f) which is the sum of rotating friction moment, sliding friction moment (M_s), and sealing friction moment (M_{se})[14]. According to the bearings catalogs, the heat generation at bearings can be obtained by the following formula:

$$Q_b = 1.05*10^{-4}.n.M_f \qquad (4)$$

Where Q_b is the bearing heat and n is the rotating speed (rpm).The friction moment M_f is calculated using certain tables and formulas which are clearly represented in.

It can be noticed from the above formula that Q_b is directly proportional to n. Hence, the heat generated through the feed drive bearings is low compared to that generated through those at the spindle head.

C. Friction heat at ball screw/nut

The heat generated at the ball screw/nut connection is due to the rolling friction occurs among them. Unlike the guide ways, the heat generated in the ball screw/nut is distributed on a narrow region which results on a larger temperature rise and larger thermal deformation for the ball screw. Similar to the sliding friction formula of the guide ways, the heat generation due to rolling friction can be obtained using the following formula:

$$Q_r = \eta.\mu.F_a.R_s.\omega \qquad (5)$$

Where Q_r is the rolling friction heat (W), η is a factor ranges from 0 to 1, μ is the rolling coefficient of friction almost equal 0.001, F_a is the axial force in the ball screw axis direction (N), R_s is the ball screw radius and ω is the angular velocity (rad/s).

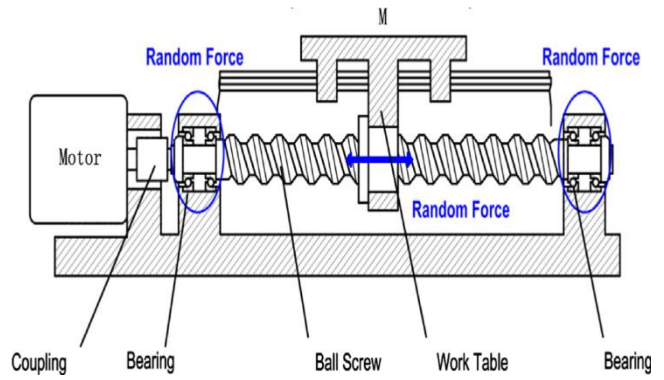


Figure 2A schematic construction of the feed drive system.

VI. HEAT GENERATION OF MACHINE TOOL SPINDLE

The spindle assembly shown in Figure 3 mainly consists of the spindle shaft, bearings, sleeves, and the driving pulley[15]. The connection between the tool holder and the tool is assumed rigid until this point of investigation. Hence, any deflection occurs on the spindle nose is assumed to be completely reflected to the TCP.

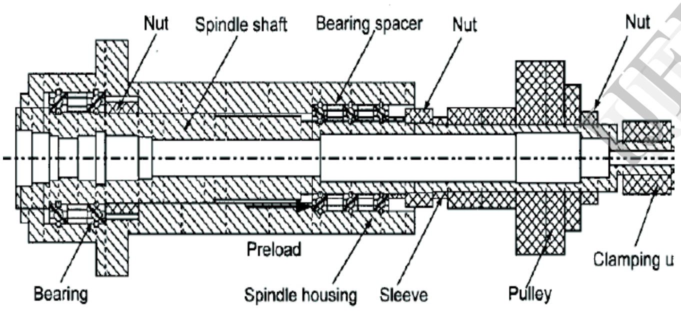


Figure 3Sectional view for the construction of the spindle assembly

Similar to the feed drive system, the main heat sources in the spindle unit are the electric motor and the rolling bearings carrying the spindle, and consequently, the same formulas can be used. It should be noted that the rotational speed of the spindle unit is much larger than that of the feed drives which means larger amount of heat generation in the rolling bearings[16]. The spindle is exposed to both conduction and convection heat transfer due to bearings, electric motor, and other attachments[7]. What makes the study of the thermal behavior of the spindle system so crucial, is that the spindle thermal deformation has a direct effect on the TCP and consequently, direct effect on the product quality.

VII. HEAT GENERATION OFTHE CUTTING PROCESS

To obtain a realistic integrated simulation system, modeling of the cutting process is integrated with the modeling of machine tool mechanical components discussed in the previous subsections. This integration leads to a realistic representation of the overall performance of the machine tool.

The friction-heat generated due to the relative motion between the cutting tool and the work piece has a direct influence in the overall deformation of the TCP. The heat generated at various machine tool hot spots are integrated with that generated at the cutting zone to determine the thermal deformation all over the machine tool and specifically at the TCP. Consequently, the cutting temperature (T_c) is included among the data entry of the designed evaluation system.

To determine the T_c, many research works have been carried out along the decades in orthogonal and conventional cutting process such as that developed by [17]. Predicting the $T_c$is not of the interest of this paper; however, a methodology that develops an empirical formula for T_c based on experimental results as discussed in[5] is recommended. Although the formula is generated for a certain work piece material called Inconel718, the methodology can be extended to be applied on other cases. Whatever is the methodology used to predict $T_{c,}$ the obtained value is then transferred to the steady state thermal analysis module at which it is assigned to the TCP.

VIII. CUTTING LOAD GENERATION

In order to study the total deformation of the milling machine and the local deformation at its TCP, the thermal deformation occurred due to various thermal loads on the machine are combined together with the static deformation occurred due to cutting loads. Many works have been carried out on different aspects linked to cutting loads prediction. Recently, researchers used FEM to simulate the chip generation and hence, predict the cutting forces and the chip morphology like those developed by[18] and [19]. However, this is not crucial to this paper. Therefore, an analytical method developed by [20]which was developed for conventional end-milling operationshas been used instead.

IX. CONSTRUCTION OF THE EVALUATION SYSTEM

One of the main design considerations of the desired evaluation system is the ability to deal with the widest range of varieties. To obtain such system, all characteristics related to both cutting temperature and the machine hot spots are put in a parametric form. When the effect of certain parameter is of interest, user can simply enters a list of its values and observes its effect on the results. The system's GUI is a data entry panel integrated in Ansys® as shown in Figure 4. The panel is divided into three areas as shown in the figure. The system inputs and outputs are defined in Area1, the design points at which the system runs are assigned in Area2, and finally, Area3 shows the charts that represent a certain relation between specified parameters. All input data and design points that are defined in Area1 and Area2 are automatically transferred to carry out the corresponding analyses without any need to log in any of the modules; then the generated results are transferred back to be displayed.

The data entry of the system and the generated results are represented in Table 1.The data is classified to that related to the machine tool which is the material thermal properties and heat generation at hot spots, and other related to the cutting process which is the cutting temperature T_c.

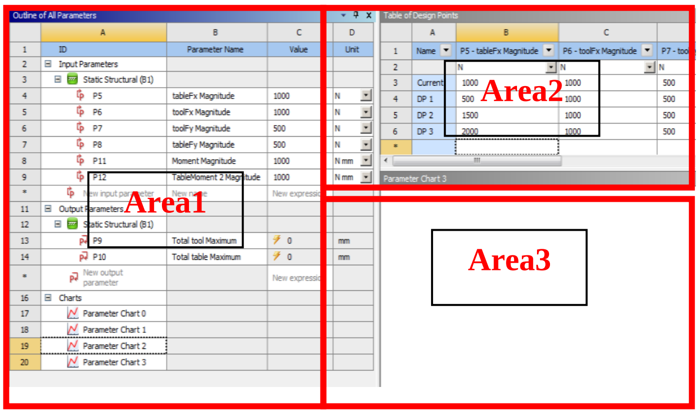


Figure 4A sample of the input/output panel of the designed evaluation system.

System entries	Obtained results
Heat generation (Q) at various hot spots of the machine tool	Temperature field and thermal deformation
Cutting temperature (T_c) at TCP	X and Y deformation at TCP
Coefficient of thermal conductivity	
Specific heat (J/Kg. C^o), and Coefficient of thermal expansion.	
Air convection coefficient W/mm^2.C^o	

Table 1 The evaluation sytem entries and obtained thermal results.

X. APPLICATION

A. Case definition

The virtual evaluation system is applied on a 3-axis milling machine tool of open category. The material of the machine structural components was assigned as gray cast iron with modulus of elasticity of 89 GPa; density of 7250 kg/m^3; and Poisson's ratio of 0.25. The milling machine electric motor is 2 HP. The ball screws are 60 mm diameter made of steel and the machine base material is concrete. On the other hand, the cutting process is carried out on work piece material called Inconel718, with cutting conditions [radial depth of cut (a) =1 mm, axial depth of cut (b) =1 mm, feed rate (u) =100mm/min, feed per tooth (f_z) =0.025 mm/tooth, and cutting speed (s) =1000 rpm], using an end mill of radius (r) =10mm, number of teeth (n) =4, and helix angle (ß) =pi/6.

B. Preprocessing

On this stage, all input data needed for the steady state thermal analysis module are determined. Heat generation due to sliding over guide ways, electric motors of feed and speed drives, friction moment at rolling bearings, rolling friction at screw/nut connection, and the cutting process are calculated using the theories previously discussed.It also should be considered that the entire machine is exposed to convection heat transfer due its presence in air field at which the ambient temperature equals 22 C^o and convection coefficient of 5*10^{-6} W/mm^2.C^o.

a. Sliding friction at Guide ways

The friction heat is generated due to sliding motion occurs between bed/saddle, saddle/table, and spindle head/column. The normal force at bed/saddle and saddle/table are due to the weights of table and saddle-table assembly which are 537 kg, and 798 kg respectively. The contact pressure due to the air bearing between spindle head and column slide is assumed to be 120 KPa. The maximum sliding velocity is 0.8 m/sec which is the maximum feed rate used in the non-cutting interval. The coefficient of friction μ at υ=0.8 m/sec and moderate surface quality is equal 0.022 as proved by [6].

By using the formula previously stated, the values of friction heat generated at bed/saddle, saddle/table, and spindle head/column are 74W, 110W, and 70W respectively.

b. Heat generation at motors

According to the formula previously represented, the heat generation at the electric motor of the feed system and the spindle head is found equal 117.6 W. knowing that the motors power (P) is assumed equal 2 HP, the motor efficiency (η_m) and the heat loss percentage (η_h) are assumed equal 0.9 and 0.8 respectively.

c. Heat generation at bearings

By using the list of formulas and tables represented in bearing catalogs, the total friction moments occurred at each bearing located in both feed drives and spindle head are found equal to 97.47 N.mm and 231.6 N.mm respectively resulting in a heat generation equal to 2.04 W and 24.3 W respectively.

d. Rolling friction at screws/nuts

The rolling coefficient of friction is assumed equal to 0.001 in case of ball screws as stated in. The maximum angular velocity of any of the ball screws is 20.94 rad/sec. The friction moment is depending on the ball screw diameter and the driving force needed to move the sliding part. The heat generation at the ball screw/nut connection is found equal to 1.6 W as found from the formula previously stated.

e. Cutting heat temperature

The cutting temperature T_c for Inconel 718 work piece material can be obtained by the following formula:

$$T_c = -124.37+0.4542V_c+71.67f_z+177.67ap+141.15ae\ (C^o) \quad (6)$$

Where V_c is the cutting speed (m/min), f_z is the feed per tooth (mm/tooth), ap is the axial depth of cut (mm), and ae is the radial depth of cut (mm). By using the above formula, the T_c is proved to be 224.76 C^o.

f. Cutting loads

According to the cutting conditions previously stated in the case definition, the cutting loads generated using analytical methods are simulated as two static components subjected to the TCP in X and Y directions with values equal to 1000 N and 500 N respectively.

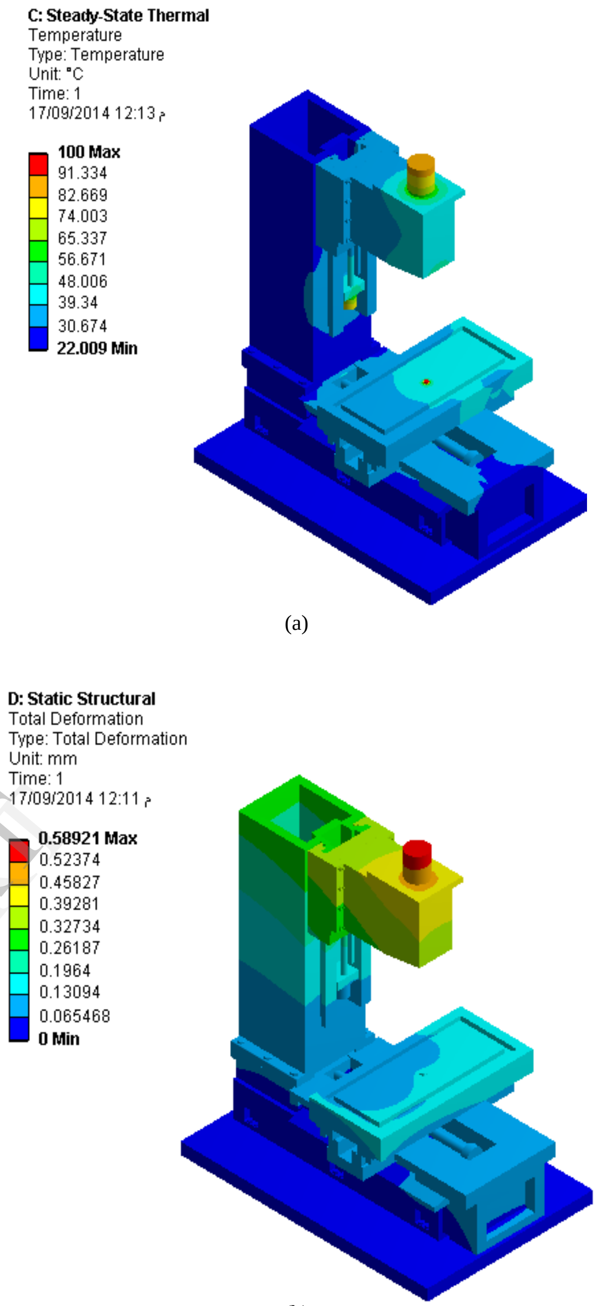
C. Static analysis results

The static analysis performed on the machine tool when subjected to loads previously mentioned shows that the x-deformation at TCP relatively to worktable is equal to 30.7 µm, while the y-deformation is equal to 7.1 µm.

D. Thermal analysis results

As evident from the temperature field of the entire milling machine shown in Figure 5 (a), the TCP shows the maximum temperature of 100 C^o, the guide ways and screws show a temperature ranges from 30 to 45 C^o, and the spots near the motors and drives show a higher temperature up to 65 C^o. On the other hand, Figure 5 (b) shows the total deformation all over the milling machine results from both static and thermal load combined together. The directional deformation at TCP is proved equal to 52 µm and 63 µm in X and Y-directions respectively; which are greater than those resulted in case of static load only.

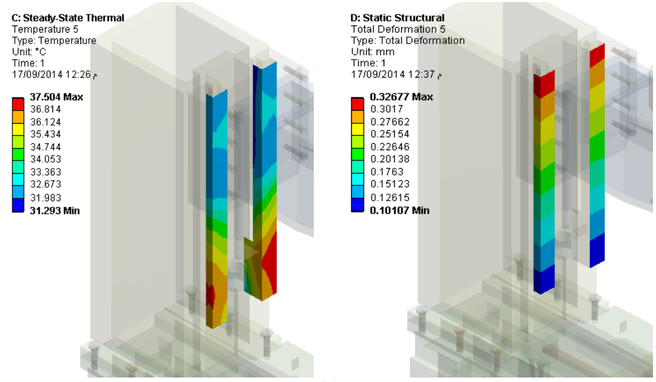
The temperature field of the three guide ways together with the combined deformation of each is represented in Figure 6. The down most region of the column slide shows the maximum temperature 37.5 C^{o}due to its close from the feed drive. On the same context, the temperature field of the three screws together with the combined deformation of each is represented in Figure 7. The maximum temperatures on the machine screws are noticed in the screw/nut connections which are 48 C^o, 48.7 C^o, and 41C^o in Z-screw, X-screw, and Y-screw respectively. The temperature at the screw supports ranges from 31C^o to 45 C^o due to the effect of heat generated from bearings and drives.



(a)

(b)

Figure 5 (a) Temperature field of the milling machine (b) the total deformation due to both static and thermal load.



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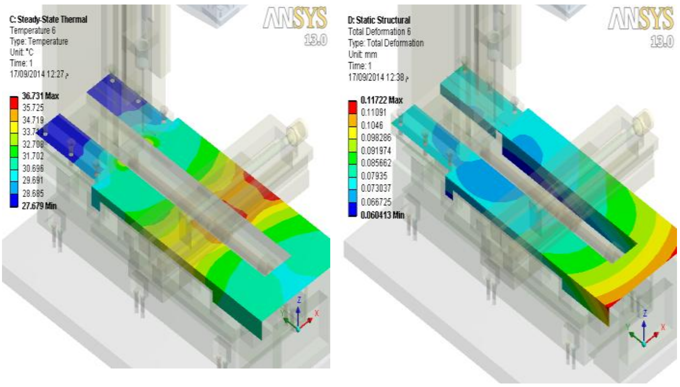

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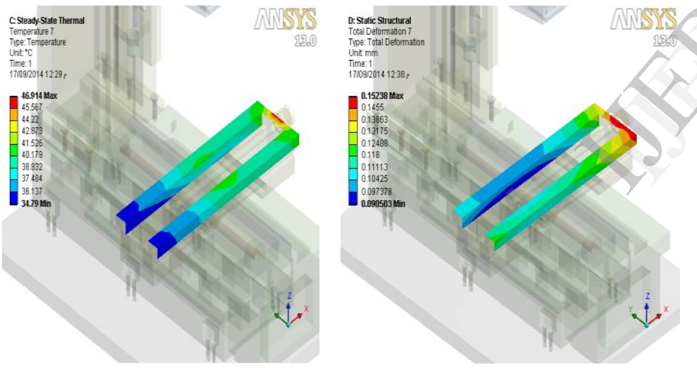
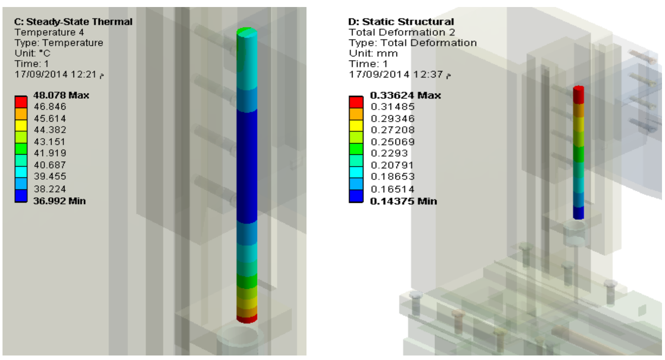


(c)

Figure 6 Temperature field and total deformation due to static and thermal load for (a) Column slide, (b) Bed slide, and (c) saddle slide.



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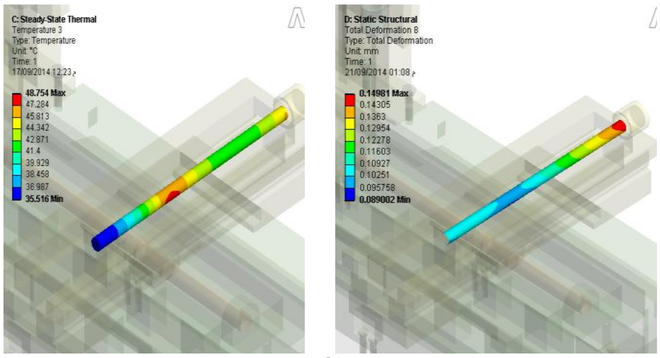

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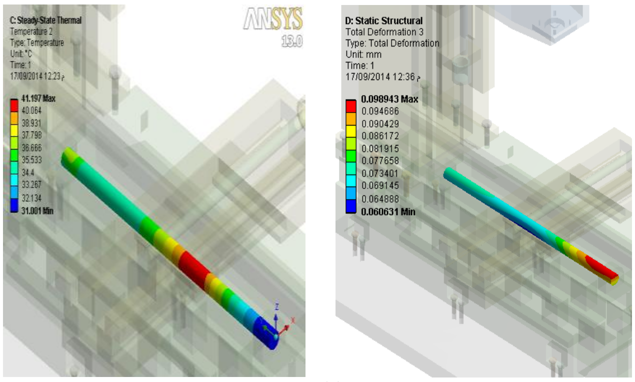

(c)

Figure 7Temperature field and total deformation due to static and thermal load for (a) Z-screw, (b) X-screw, and (c) Y-screw.

XI. CONCLUSION

An integrated modeling and design approach is developed to create a virtual evaluation system capable to evaluate the thermal performance of 3-axis milling machine during its design stage without the need of prototyping. The modeling of the machine tool mechanical structures and the heat generation at the hot spots together with the modeling of the heat generation of the cutting process are all integrated together to evaluate the thermal performance of the entire machine tool. The system is then applied to a case study and the results are represented and discussed in details. The screws are proved to be the most critical elements while studying the thermal behavior of the machine tool due to its high temperature and low size. In future work, the thermal deformation of the slides and screws which are obtained from the analyses can be used to determine the sliding errors and hence, the product error.

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