THE EFFECT OF HEAT GENERATED BY FRICTION IN THE BALL-SCREW-NUT SYSTEM ON THE PRECISION OF HIGH SPEED MACHINE[+]

Mahmmod Aziz Muhammed [*]

Abstract:

High Speed Machining (HSM) offers the promising choice for increasing industrial demands. However, HSM implies more reciprocating movement in machine tool axes. Friction forces, which occur in highly speed moving components, such as ball-screw assembly subjected to linear motion, will induce heat. Factors such as cutting forces, material weight, feeding acceleration, etc, decide how much heat that will be generated and accumulated. On the other hand, positioning sensor used in HSM, which detects machine position by means of rotary encoder that is mounted on the same axis with the screw-nut assembly, is mostly indirect positioned. Machine position is determined by converting rotary encoder signal and ball screw's lead into linear translation position. Accordingly, positioning error will occur when lead is not uniform in motion or there is a change in lead when machine is being operated.

In this research, heat generation due to friction forces induced in the ball-screw-nut assembly is studied. The aim is to understand the phenomenon of heat accumulation that may affect positioning errors due to lead-elongation. Additionally, the deformation caused by temperature increase is estimated based on temperature distribution within the ball-screw assembly which is determined numerically applying the conventional finite difference method.

Keywords: HSM, Heat Generation, Friction, ball-screw assembly, positioning error, finite difference method.

تاثير الحرارة المتولدة بسبب الاحتكاك في نظام عمود الدوران المسنن والصامولة المزودة بكريات على دقة المكائن عالية السرعة

محمد عزيز محمود

المستخلص:

تعتبر المكائن عالية السرعة الاختيارالامثل لاستيفاء الطلب المتزايد على الصناعة. مع ذلك،هذه المكائن تتضمن حركات ترددية في محاور عدد القطع تؤثر سلبا في استحداث قوى احتكاك في السرع العالية والتي بدورها تؤدي الى نشوء حرارة مستحثة وبالتالي حدوث تشوه في الأجزاء المتحركة في الماكنة (نظام الصامولة وعمود الدوران المسنن المعرضة لحركة دورانية وخطية في ان واحد مثال لهذه الاجزاء). عوامل مثل قوى القطع،وزن المادة الخام،معدل التغذية،الخ، ستحدد كمية الحرارة المستحثة والمتراكمة. من جهة اخرى، مجس تحديد موصع عدة القطع عن طريق قارئ بيانات دوار يقع على نفس المحور مع عمود الدوران المسنن والصامولة مما يؤدي الى تاثرقرائتة بالتشوه الحراري الحاصل. ونتيجة لذلك، هذا الخطا في موضع عدة القطع سيؤثرسلبا على دقة ابعاد المنتج وبالتالي اختلاف عن الابعاد التصميمية للمنتج النموذجي.

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[*] **Lecturer / Technical Institute / Amara .**

في هذا البحث تم حساب الحرارة المستحثة بسبب الاحتكاك الحاصل في نظام عمود الدوران المسنن والصامولة ومن ثم حساب التشوه الحاصل نتيجة للاحتكاك الحاصل عن طريق تحديد توزيع درجة الحرارة في الاجزاء المتحركة الذي تم الحصول عليه بتطبيق طريقة الفروقات المحدودة.
الكلمات الدليلية:مكائن عالية السرعة،الحرارة المتولدة، الاحتكاك،مجموعة الأسنان والكرات،الخطأ الموضعي،طريقـــة الفرو قات المحدودة

Introduction:

Ball Screw assemblies (BSA's) are important components in modern CNC machine tools that convert rotary motion into linear motion. They comprise a Ball Screw, with an external helical groove or raceway, a Ball Nut, with an internal helical groove or raceway, and a system for re-circulating balls, which are rolling elements fitted between the Ball Screw and the Ball Nut (See Figure 1).

Figure (1) Ball-Screw-Assembly (BSA)

BSA's are supplied in different lead accuracies, with or without pre-load depending upon the application. There are also different pre-loading methods - for machine tools, BSA's will usually have a two point angular contact pre-load.
In machine tools, BSA's most commonly drive each of the three axes (x, y, z) coupled with a servo-motor and encoder. Standard CNC machines are fitted with a control which is linked to the servo motor and encoder, but more expensive machines may also have linear feed-back via a scale attached to the axis. The servo-motor can make very small angular movements which, when coupled with the BSA, moves the axis as little as 1μm. Clearly, positional accuracy and repeatability of the BSA is an important part of overall machine tool accuracy.

The Failure of Ball Screw Assembly:

BSA's fail for a number of reasons:

- **Fatigue wear:** this wear occurs when the surface of a material is weakened by repeated cyclic loading resulting in material fatigue. See Figure (2):

Figure (2) The effect of fatigue on ball nut surface

- **Adhesive Wear:** Ball Screws have traditionally been designed using conventional materials. The Ball Screw and Ball Nut are most commonly manufactured in bearing steel and the rolling elements (balls) are manufactured in carbon chrome steel. However, during any sudden acceleration or change of direction, conventional rolling elements will not have a true rolling motion but will initially be prone to sliding and galling. This leads to adhesive wear and micro or cold welding because of the steel-ball-to-steel-raceway interaction, where surface projections, or asperities, are plastically deformed and eventually welded together by the high local pressure. See Figure (3).

Figure (3) The effect of adhesive wear on Ball surface

- **Positional Accuracy Error**: a BSA's life can be considered in another way, known as its 'wear life' - the number of revolutions it can make before its positional accuracy deteriorates. For machine tool designers and maintenance engineers, wear life is an important factor to consider, as this will gradually deteriorate over time. This is especially evident in today's machine tools, which increasingly need improved positional accuracy, increased acceleration and linear speed.
  However, there are many extraneous variables which affect the life of a BSA in the field, such as contamination, incorrect lubrication, misalignment, or even application errors. In this research, we will be concerned with the positional accuracy error because it has something related to heat generated by friction which in its turn caused by the high speed motion.

The heat generated by friction:

High speed forces the moving components including BAS to work harder; hence friction between two moving components will induce heat flux which represents the initiation of thermal deformation. On the other hand, CNC machines which use indirect positioning are mostly facilitated with pitch compensation error. Error compensation, which represents the input to the control unit, is measured using absolute measurement and compared to the value displayed on the monitor. According to the way the error compensation is input, the deformation caused by heat generation is not yet in indirect measurement system such as rotary encoder. Apprehensive deformation will influence the product dimensions, so it needs to be controlled after knowing temperature distribution in the moving components, namely BAS which is prone to thermal deformation and hence becoming the source of error in product dimensions.

This research is trying to determine the temperature distribution in ball-screw-nut system on CNC machines using finite difference method. Having known this temperature distribution, thermal deformation is consequently calculated.

Basic theory:

When a temperature gradient exist in a material, experience has shown that there is an energy transfer from high temperature region to the lower temperature region which is called as transferred energy by conduction. Conduction can be analyzed by Fourier's law [4], that is:

$$q = -kA\frac{dT}{dx} \tag{1}$$

Where q = heat transfer rate of conduction (W), k = thermal conductivity of material (W/m.ºC), A = surface space of material (m^2), dT/dx = temperature gradient in the direction of heat flow (ºC/m).

Consider a material of cylindrical shape in which cylindrical system of coordinates is used in analysis. When one-dimensional heat transfer is assumed in radial direction, conduction equation can be expressed as follows [4]:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2}$$

Where r = the cylinder radius (m), α = $k/\rho c$ referred to as thermal diffusivity (m^2/s), c = specific heat of material (J/kg.ºC), and ρ = density of material (kg/m^3).

Convection heat transfer is formulated using Newton's law of cooling which states that [4]:

$$q_c = h_c A(T_s - T_{surr}) \tag{3}$$

Where h_c = the convection heat transfer coefficient (W/m^2.ºC), T_s = surface temperature of material (ºC), T_{surr} = temperature of surroundings (ºC).

Almost all solids expands upon heating, the expansion is sufficiently uniform so that the length is a linear function of temperature. Thus, the change in length, which is proportional not only to the change in temperature but also to the original length L, is expressed as follows [5]:

$$\Delta L = \alpha_t (\Delta T) L \tag{4}$$

Where α_t = coefficient of linear expansion, ΔT = temperature accretion (ºC), L = material length (m), and ΔL = length accretion (m).

Finite Difference Method:

The parabolic equation (equation 2) derived from the theory of heat conduction has a solution which, for instance, gives the temperature T at a distance r units of length from one end of a thermally insulated bar after t seconds after heat conduction has passed through the bar. In such a problem, temperatures at the end of a bar with a length of l are often known at any time. In other words, the boundary conditions for our problem are known. It is also usual for the temperature distribution along the bar to be known at some particular instance. This instance is usually taken as zero time at which the temperature distribution is called initial condition.

The area of integration S in r-t plane (Figure 4), is the infinite area bounded by r-axis and the parallel lines $r = 0$ and $r = l$. This is described as an open area since the boundary curves marked C do not constitute a closed boundary in any finite region of r-t plane.

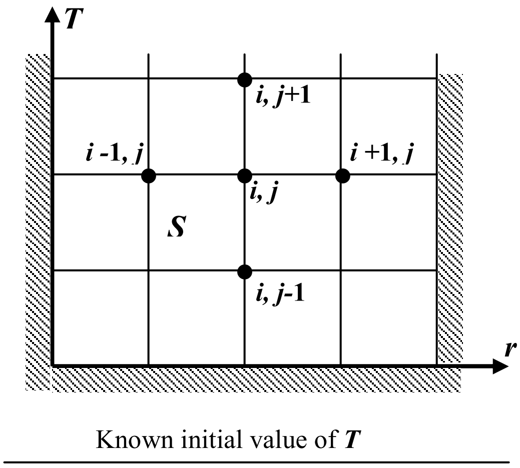

Figure (4) Quantification node on $r – t$ space

In finite difference method, the area of integration of the parabolic equation is overlaid by a system of rectangular meshes formed by two sets of equally spaced lines; one set is parallel to $0r$ and the other is parallel to $0t$. The approximate solution to the differential equation is found at the points of intersection $i -1, j,\ i, j,\ i, j+1$, ….of the parallel lines. Those points are called mesh points [6].

Finite differences are substituted for the derivative in the original equation (equation 2). Thus, the differential equation is transformed into a set of simultaneous algebraic equations. Finite difference approximation shown as these formulations [7]

$$\frac{\partial T}{\partial r} = \frac{T_{i+1}^{j} - T_{i-1}^{j}}{2(\Delta r)} \tag{5}$$

$$\frac{\partial^2 T}{\partial r^2} = \frac{T_{i+1}^{j+1} - 2T_{i}^{j+1} + T_{i-1}^{j+1}}{(\Delta r)^2} \tag{6}$$

Equations (5) and (6) are referred to as first and second derivative of central difference.

Model:

Model is required before the problem can be analyzed and calculated. In this research, two models are studied, these are; machine tool mechanism model and activator component model.

Mechanism tool of machine tool:

Primary motion concept of moving components incorporated in machine tool is converting rotation to linear motion by a motor using the thread actuator (lead screws) [8]. Motion which is performed by nut and shaft will generate friction. Consequentially, heat induced within machine components that can affect deformation against screw shaft and nut. Hence, machine becomes less precise and the product will have dimensions that are not accepted according to the expected quality.

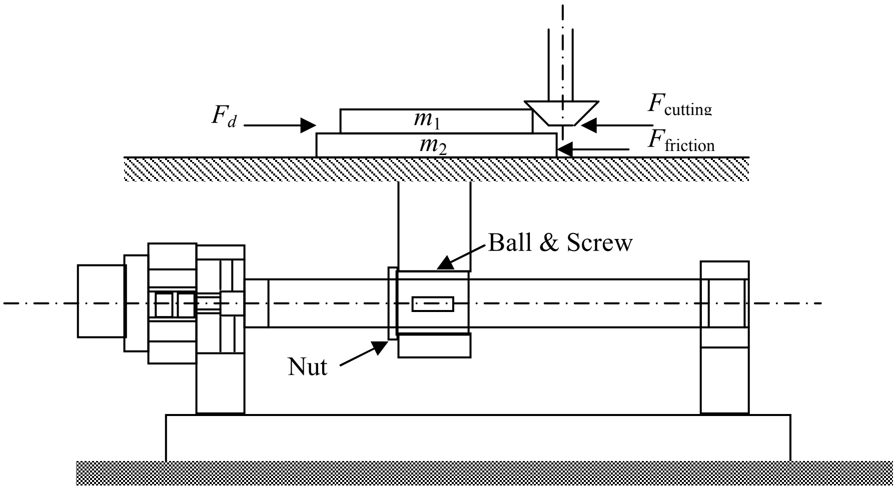

Figure (5) Forces acting on ball-screw-nut assembly

Forces on cutting tool

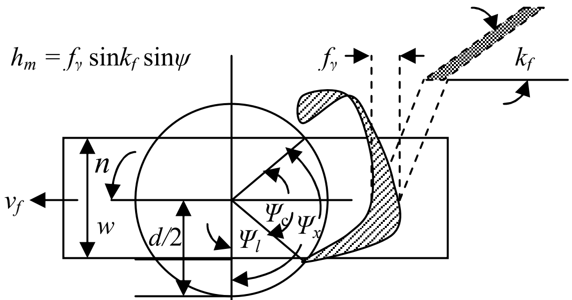

Figure (6) Chip removal and geometry

Cutting force is determined by the produced chip forms during machining processes and is formulated as follows [9]:

$$F_{ims} = K_{s1,l}\, w (h_m)^{l-p} .Zc \tag{7}$$

Where $K_{s1,l}$ = specific cutting force (N/mm^2), w = chip width (mm), h_m = thickness average of chip (mm), k_f = cutting angle, and Zc = effective tooth.

As an alternative way, cutting force can be found using the power and rotation of spindle as follows:

$$P = \frac{F_{tms} .\pi .d .n_{spindle}}{60.000.000} \tag{8}$$

Where P = power of spindle (kW), F_{tms} = cutting force (N), d = tool diameter (mm), $n_{spindle}$ = rotation speed of spindle (rpm).

Total force occurred when ball-screw and nut are rotated. This rotation causes friction which in its turn influences the torque that act upon moving components. The friction force will generate heat flux which can be formulated as follows [9]:

$$q_0 = \frac{T .n_{actuater} .0.1047}{r_{shaft} .L_{nut}} \tag{9}$$

Where T = torque (N.m), $n_{actuator}$ = rotation speed of actuator (rpm), r_{shaft} = radius of shaft (m), L_{nut} = length of nut (m).

Model of moving components:

The research focuses on moving components of machine tool in the sake of high precision. Those components are ball-screw-nut assembly which movement can be described as follows [10]:

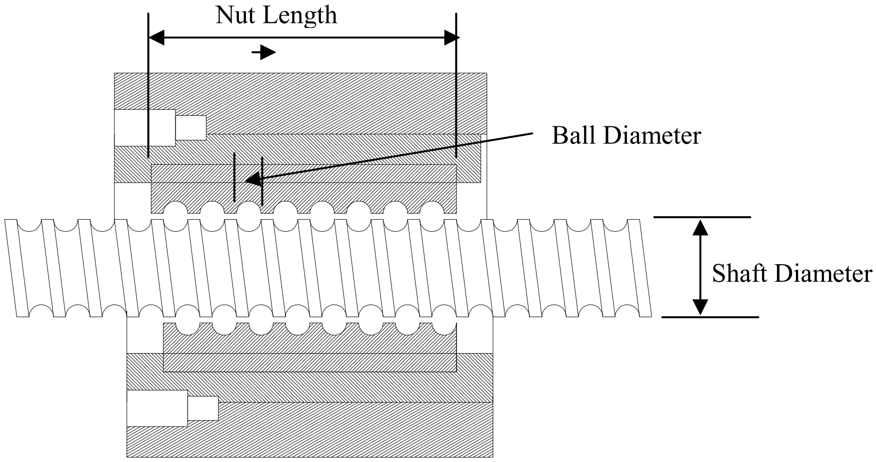

Figure (7) Ball-Screw-Nut System

To simplify analysis, ball-screw assembly is modeled as a solid straight cylinder with no thread while nut is modeled as a hollow cylinder with no thread. The model is shown below:

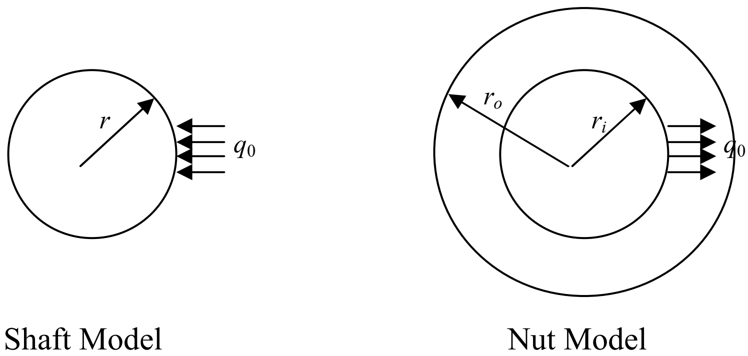

Figure (8) Analysis Model of Ball-Screw-Nut System

Initial and boundary conditions:

Initial condition is the nut was kept at room temperature, that is $T(r,0)$ = 25ºC, while the boundary conditions for the nut can be formulated as shown in the following equations:

$$q_0(1+\frac{1}{e^t}) = -k\frac{\partial T}{\partial r}\bigg|_{r=r_i} \tag{10}$$

$$-k\frac{\partial T}{\partial r}\bigg|_{r=r_{out}} = h_c(T_s - T_{surr}) \tag{11}$$

the initial conditions at the shaft itself is given by:

$$T_{(r,t)} = k_0(1-(\frac{\Delta r}{r_{out}})^2) + T_{surr} \quad (12)$$

where k_0 is a constant which

The boundary conditions of the shaft can be expressed by the following two equations [6]:

$$k\frac{dT}{dr}\Big|_{r=r_0} = 0 \quad (13)$$

$$k\frac{dT}{dr}\Big|_{r=r_i} = h_c(T_s - T_{surr}) \quad (14)$$

<u>Temperature Distribution of Moving Components</u>:

During our analysis, the following conditions are applied:

- Temperature gradient is assumed to be in radial direction
- Friction occurred will induce constant heat flux at moving components which are in contact.
- Material of the shaft and nut have constant thermal conductivity and
- No heat generation in all moving components.

Now, using equation (2) will give the temperature distribution in the numerical space which is divided into many grids *i* and *j*. The resulting equation can be written as shown below:

$$\frac{T_{i+1}^{j+1} - 2T_i^{j+1} + T_{i-1}^{j+1}}{(\Delta r)^2} + \frac{1}{2i\Delta r}\frac{T_{i+1}^{j+1} - T_{i-1}^{j+1}}{\Delta r} = \frac{1}{\alpha}\frac{T_i^{j+1} - T_i^j}{\Delta t}$$

which after simplification becomes:

$$T_i^j = -(m+n)T_{i+1}^{j+1} + (2m+1)T_i^{j+1} - (m-n)T_{i-1}^{j+1} \quad (15)$$

Where:

$$m = \frac{\alpha\Delta t}{(\Delta r)^2} \text{ and } n = \frac{\alpha\Delta t}{2i(\Delta r)^2}$$

If the initial and boundary conditions of nut and ball-screw are put into equation (15) we will have the following equations:

For the center of shaft:

$$-(2m+1)T_{i,j+1} + 2mT_{i+1,j+1} = -T_{i,j} \quad (16)$$

For the outer surface of the shaft:

$$2mT_{i-1,j+1} - (2m+1)T_{i,j+1} = -T_{i,j} + m(1+\frac{1}{2i})q_0(1+\frac{1}{e^t})\frac{2\Delta r}{k} \quad (17)$$

For the inner surface of nut:

$$-(2m+1)T_{i,j+1} + 2mT_{i+1,j+1} = -T_{i,j} - m(1-\frac{1}{2i})q_0(1+\frac{1}{e^t})\frac{2\Delta r}{k} \quad (18)$$

For the outer surface of nut:

$$2mT_{i-1,j+1} - \left[2m+1+m(1+\frac{1}{2i})\frac{2\Delta rh}{k}\right]T_{i,j+1} = -T_{i,j} - m(1+\frac{1}{2i})\frac{2\Delta rh}{k}T_\infty \quad (19)$$

and hence will yield thermal deformation analysis for moving components.

Analysis Result:

All analysis results are the outputs of programs which run using MATLAB. Those output show the temperature distribution within the moving components which are in contact at certain moment of time. Machine's operating conditions in all cases are:
Spindle speed = 30000 rpm,
Power of spindle = 11 Kw,
Feeding speed, $V_f = 30$ m/min,
moving component acceleration, $a = 2$ m/s^2,
$r_i = 0.02$ m, $r_{out} = 0.041$ m,
$L_{shaft} = 1.300$ m
Let us begin with ball-screw-nut assembly which its temperature distribution is shown in Fig. (9) where the values of temperatures for both shaft and nut is shown in Table (1).

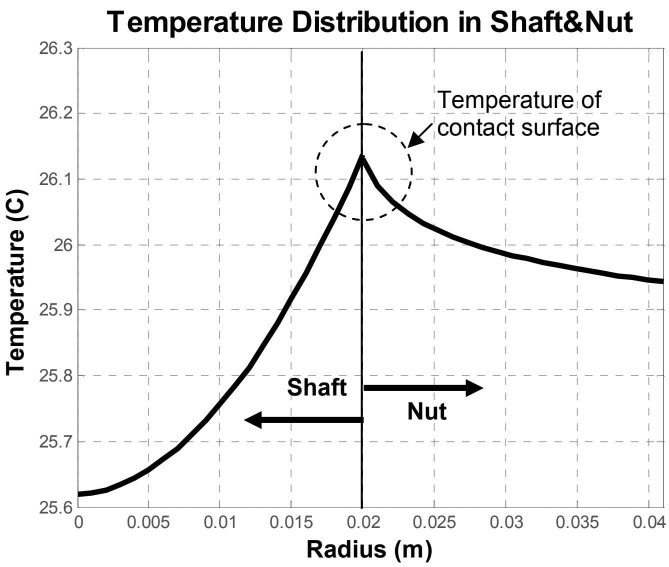

Figure (9) Temperature Distribution in Shaft-Nut Assembly

Based on the figure above, thermal deformation caused by the change in temperature of nut can be calculated as follows:
$\Delta r_i = 12\times10^{-6}(36.3 - 25)\ 0.02 = 2.712\times10^{-6}$ m
$\Delta r_{out} = 12\times10^{-6}(36.3 - 25)\ 0.041 = 5.5596\times10^{-6}$ m
Subsequently, deformation in nut is:
$\Delta L = 12\times10^{-6}(36.3 - 25)\ 0.072 = 9.7632\times10^{-6}$
In the same way, thermal deformation in shaft can be evaluated as follows:
$\Delta r_i = 12\times10^{-6}(32.4 - 25)\ 0.02 = 1.776\times10^{-6}$
$\Delta L = 12\times10^{-6}(36.3 - 25)\ 1300 = 0.17628$ mm

Table (1) the temperatures of both shaft & nut

r_s	r_n	Shaft	Nut
0	0.021	25.6185	26.1314
0.0010	0.022	25.6209	26.0897
0.0020	0.023	25.6261	26.0646
0.0030	0.024	25.6338	26.0467
0.0040	0.025	25.6441	26.0328
0.0050	0.026	25.6568	26.0215
0.0060	0.027	25.6719	26.0118
0.0070	0.028	25.6895	26.0035
0.0080	0.029	25.7094	25.9961
0.0090	0.030	25.7318	25.9895
0.0100	0.031	25.7565	25.9836
0.0110	0.032	25.7837	25.9781
0.0120	0.033	25.8132	25.9731
0.0130	0.034	25.8452	25.9685
0.0140	0.035	25.8796	25.9642
0.0150	0.036	25.9163	25.9602
0.0160	0.037	25.9555	25.9564
0.0170	0.038	25.9971	25.9528
0.0180	0.039	26.0411	25.9495
0.0190	0.040	26.0875	25.9463
0.0200	0.041	26.1363	25.9432

r_s is the shaft radius and r_n is the nut radius

By changing the cutting tool geometry, temperature distribution in tool diameter within 3600s duration is shown in Fig. (10) below

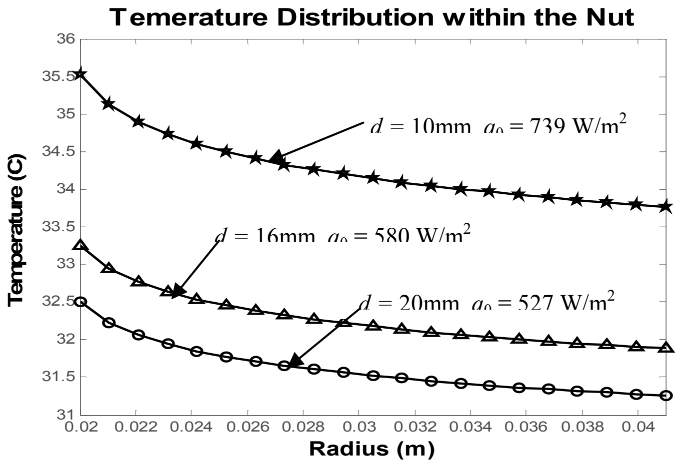

Figure (10) Temperature Distribution in Shaft-Nut System according to diameter variation

Using smaller tool diameter at the same machining process will result in temperature increase within the tool itself. This can be interpreted as follows; small tool diameter at the same touch angle between the tool and material to be machined will cause effective teeth progressively increase during machining process, hence greater force action imposed.

With the same machining condition, increasing load will consequently increase friction among components that are in contact and thus higher working temperature is expected.

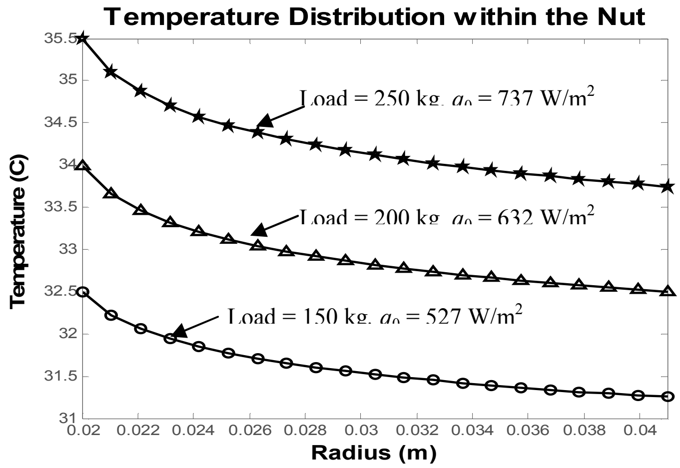

Figure (11) Temperature Distribution in Shaft-Nut System according to load variation

On the other hand, using longer lead could decrease heat flux induced in moving components. The reason is longer lead decreases shaft rotation speed and consequently less friction among moving components that are in contact occurred.

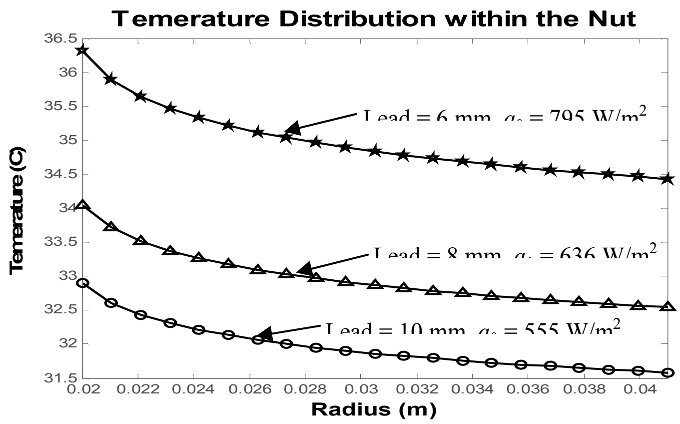

Figure (12) Temperature Distribution in Shaft-Nut System according to lead variation

Notice that at different spindle speeds, temperature distribution in nonlinear because the temperature distribution is determined by taking revolution of moving components in account.

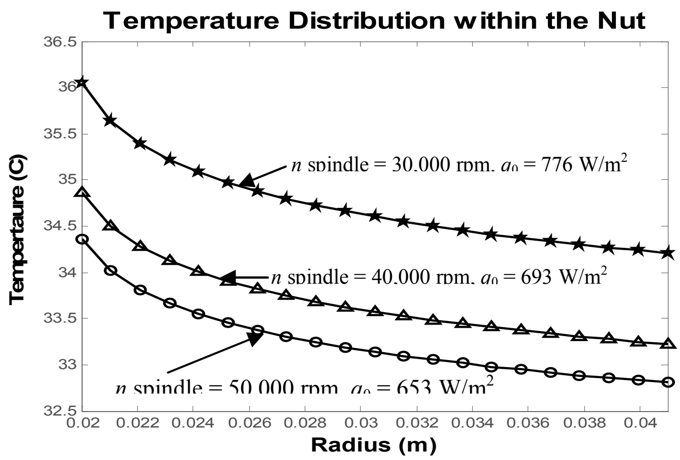

Figure (13) Temperature Distribution in Shaft-Nut System according to spindle speed variation

NOTE: All the Figures Above Have Been Drawn Though Computer Programs Using MATLAB Compiler.

Conclusion and Suggestions:

The main cause of positional error occurred in moving components which is usually encountered in high speed machines has been studied. Having done our analysis and getting the results, our conclusions and suggestions can be summarized below:

- The main cause of heat generation in the rotating component is the friction induced by adhesive wear. This can be explained as follows; as the sliding on the surfaces in contact continues, the bonds initiated by cold welding which is caused by adhesive wear are broken, producing cavities on the surface, projections on the second surface, and frequently sub-micron abrasive particles - all of which contribute to future wear in surfaces causing surface roughness, excessive heat and eventual Ball Screw failure.
- Even though the deformation caused by heat generated is so small, for example the difference in the dimension of internal radius of nut is only 2.7 μm, this difference will be so significant and influential on the products shaped in CNC machines because, as we mentioned early, the movements of nut are only few micrometers.
- One way to improve the service life of traditional BSA's is to have them serviced at regular intervals, replacing the worn rolling elements, super finishing the raceways and re-preloading the assembly. This will increase the life significantly (if not left too late and material fatigue has not already occurred) and will also improve the positional accuracy.

References :

1- Kleis I. and Kulu P.: *Solid Particle Erosion*. Springer-Verlag, London, 2008.
2- Gahr K.-H.: *Microstructure and wear of materials*, Elsevier, Amsterdam, 1987.
3- Taniguchi .N, "On the Basic Concept of 'Nano-Technology'," *Proceeding of International Conference*, London, Part II, British Society of Precision Engineering, 1974.
4- Holman, J. P., *Heat Transfer*, McGraw-Hill Inc., New York, 1981.
5- Halliday, David, Resnick, and Robert, *Physics*, Erlangga, Jakarta, 1996.
6- Smith, G. D. and Ganale, R. P., *Numerical Solution of Partial Differential Equations: Finite Difference Method*, Oxford University Press, New York, 1985.
7- Chapra, S. P. and Ganale, R. P., *Numerical Methods for Engineers*, McGraw-Hill Inc., New York, 1985.
8- Nersauae,D, "Precision Machine Components", *NSK Singapore (Private) LTD*, Vol.35, N0.3, pp.46-66, 2004.
9- Rochim and Taufiq, "Teori dan Teknologi Proses Pemesinan", *Proceeding of the 3rd Higher Education Development Support*, Bandung, Indonesia, 1993.
10- Hiwin, *Ball-Screws Technical Information*, Bangkok University Press, Taiwan, 2004.