# FINITE ELEMENT ANALYSIS OF THE FEED DRIVE SYSTEM OF A CNC M/C CENTER

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**Abstract**

Precise positioning systems with high speed, high resolution and long stroke become more important in ultra-precision machining. The development of high-speed feed drive systems has been a major issue in the machine-tool industry. A high-speed feed drive system reduces necessary non-cutting time. However, due to the backlash and friction force between the ball screw and the nut, it is difficult to provide a highly precise feed drive system.

A high speed drive system generates more heat through friction, at contact areas, such as the ball screw and nut. There by causing thermal expansion,which affects the machining accuracy. Therefore the thermal deformation of a ball screw is one of the most important objects to consider for high accuracy and high speed machine tools. The objective of this project is to analyze the temperature increase & the thermal deformation of a ball screw feed drive system using Finite Element Analysis.

**Keywords:** Ball Screw and Nut.

## *I. INTRODUCTION*

The demand for high-speed/high-precision machine tools is rapidly increasing in response to the development of production technology that requires high-precision parts and high productivity.

Research on high-speed machine tools can be approached from two directions. The main spindle or the feed drive system. In this research, a high-speed feed drive system was investigated in order to achieve rapid travel with improved precision. A high-speed feed drive system reduces non-cutting time and tool replacement time, making production more economical. However, it also generates more heat through friction at contact areas such as the ball screw and the nut, causing thermal deformation that subsequently degrades the accuracy of the machine tool. With this in mind, the thermal behavior of a feed drive system was investigated in order to develop a systematic method of analysis.

Most current research is focused on the thermal error compensation of the whole machine tools. Thermally induced error is a time-dependent nonlinear process caused by non-uniform temperature variation in the machine structure. The interaction between the heat source location, its intensity, thermal expansion coefficient and the machine system configuration creates complex thermal behavior. A high-speed drive system generates more heat through friction at contact areas, such as the ball screw and the nut, thereby causing thermal expansion, which adversely affects machining accuracy. Therefore, the thermal deformation of a ball screw is one of the most important objects to consider for high-accuracy and high-speed machine tools.

In order to achieve high precision positioning, preload on the ball screw is necessary to eliminate backlash. Ball screw preload also plays an important role in improving rigidity, noise, accuracy and life of the positioning stage. However, preload also produces significant friction between the ball screw and the nut that generates greater heat, leading to large thermal deformation of the ball screw and causing low positioning accuracy. Consequently, the accuracy of the main system, such as a machine tool, is affected. Therefore, an optimum preload of the ball screw is one of the most important things to consider for machine tools with high accuracy and great rigidity. Heat induced due to friction is the main source of deformation in a ball screw system; the heat generated being dependent on the preload, the lubrication of the nut and the assembly conditions.

The proposed FEM model was based on the assumption that the screw shaft and nut are a solid and hollow shaft respectively. The objective of this work was to analyze the temperature increase and the thermal deformation of a ball screw feed drive system. Finite element method was applied to simulate the thermal behavior of the ball screw.

### A. Lead Screw

The lead screw corresponds to the principle of screw-nut combination. However the screw and the nut respectively are highly precise manufactured. In combination with particular thread pitch and corresponding choice of material static and sliding friction can be reduced to minimum. In spite of high quality of manufacture the lead screw shows some axial backlash. This can be eliminated with help of preload. A limited lifetime is due to friction of the sides of threaded nut and threaded screw. The lead screw is not suited for highly static and dynamic loads.

### B. Ball screw

Balls roll on a ground or rolled shaft, having a helical groove. The balls support themselves in a helical groove with same pitch which is incorporated in the nut. Due to the revolving shaft the balls roll in the groove and move the nut (if not revolving) one screw pitch per rotation (further). The nut incorporates a recirculation system returning the balls that arrived at the end to the beginning of the nut. This model allows execution of linear motions by rotatory movements. This ball screw shows high efficiency. Stick-slip effect does not occur. Due to selected balls a thread-nut combination with zero backlash can be achieved.

### C. Ball Screw Feed Drive System

A ball screw is just that a screw which runs on balls. The screw and nut have matching helical grooves or races, and the ball bearings re-circulate in these races. There is no physical contact between the screw and the nut. As the screw or nut rotates, and the rolling balls reach the trailing end of the nut, they are deflected or guided from this "pitch" contact by means of a return tube and returned to the leading end of the circuit. There, the cycle resumes and the balls re-circulate continuously.

The ball screw is a simple device for transmitting power mechanically. It is an efficient converter of rotary-to-linear or linear-to-rotary motion. It is a member of the family of power transmission screws. However, it possesses many more important sales and engineering advantages than conventional screws as well as other means of power transmission.

Re-circulating ball screws reduce the sliding friction of lead screws to rolling friction. They consist of a screw, a nut (ball housing) and a number of balls riding between the screw and the nut. When the screw rotates, the revolving balls transmit an axial movement to the housing attached to the carriage. Before the balls reach the end of the thread they re-circulate to their original position through a channel in the housing. By selecting a certain ratio of ball diameter and thread diameter a backlash eliminating preload is generated.

## *II. GENERAL CONSIDERATION*

Load, stroke, life, accuracy, driving torque, backlash, stiffness, lead screw shaft diameter, etc., are the basic factor in the selection of ball screws. They are all interrelated and if one factor is changed and others also have to be changed. This entire factor must be checked carefully in order to select the most suitable types of ball screws. A larger screw diameter ensures higher stiffness, but the force of inertia increases at the same time. A smaller screw diameter will, on the other hand, reduce both the inertia and stiffness.

### A. Lead

If the lead is fine, the positioning accuracy increases and the driving torque required will be small. On the other hand, the rotating speed has to be higher in order to obtain the maximum operational speed. The system stiffness will decrease because of the necessity to use smaller diameter balls.

If the lead is coarse, it becomes possible to slowdown the rotational speed and also to obtain a higher stiffness and longer life. Because of the usage of large size balls the driving torque has to be increased and the potential accuracy will be slightly reduced.

### B. Preloading

A high preload makes it possible to obtain better positioning accuracy and higher system stiffness, but it will require a higher torque to drive the screw. If the preload is too high, the increase of the driving torque will exceed that of system stiffness, resulting in decrease of life. Too high a preload may result in less positioning accuracy. It depends on the characteristic of the servo loop. The low preload gives low drag torque but also low system stiffness and reduced positioning accuracy.

### C. ANSYS

ANSYS program is a general purpose program meaning that we can use it for almost any type of Finite Element Analysis virtually in any industry. General purpose also refers to the fact that the program can be suited in all disciplines of engineering Mechanical, Electrical, Thermal, Electromagnetic, Electronic, Fluid, Bio-Medical this is also used as an educational tool in universities and other academic institutions .ANSYS program has a comprehensive graphical user interface (GUI) that gives users easy, interactive access to program functions, commands, documentation and reference material. Intuitive menu system helper's users navigate through the ANSYS program. User can input data using a mouse, keyboard or the combination of both. The ultimate purpose of a finite element analysis it to recreate mathematically the behavior of an actual engineering system. In other words, the analysis must be an accurate mathematical model of a physical prototype. In the broadest sense, this model comprises all the nodes, elements, material properties, real constants, boundary conditions, and other features that are used to represent the physical system. In ANSYS terminology, the term model generation usually takes on the narrower meaning of generating the nodes and elements that represent the spatial volume and connectivity of the actual system. Thus, model generation in this discussion will mean the process of defining the geometric configuration of the model's nodes and elements.

Solid modeling is generally more appropriate for large or complex models, especially 3D models of solid volumes. With solid modeling, we have to describe the geometric boundaries of our model, establish controls over the size and desired shape of our elements and the instruct the ANSYS program to generate all the nodes and elements automatically. Solid modeling is usually more powerful and versatile than direct generation and is commonly the preferred method for generating our model.

It allows as working with a relatively small number of data items. It allows geometric operations (such as dragging and rotations) that cannot be done with nodes and elements. It supports the use of "Primitive" areas and volumes (such as polygonal areas and cylindrical volumes) and Boolean operations (intersections, subtractions, etc...) for "top down" construction of our model. Solid modeling facilities many design optimization features such as adaptive meshing, area mesh refinement after loads have been applied. It readily allows modifications to geometry; it facilitates changes to element distribution. However solid modeling can sometimes require large amounts of CPU time (for small and simple models).Sometimes be more cumbersome, requiring more data entries than direct generation. Can sometimes "fail" (the program will not be able to generate the finite element mesh) under certain circumstance. Direct generation is convenient for small or simple models. Provides as with complete control over the geometry and numbering of every node and every element. However, direct generation is usually too time consuming for all but the simplest models; the volume of data we must work which can become overwhelming. It cannot be used with adaptive meshing. It makes design optimization less convenient, difficult to modify the mesh (tools such as area mesh refinement, Smart sizing, etc.. cannot be used).It becomes tedious, requiring as to pay more attention to every detail of our mesh, tedium can sometimes cause as to become more prone to committing errors. With the direct generation method, we have to determine the location of every node and the size, shape and connectivity of every element prior to defining these entities in our ANSYS model. Although some automatic data generation is possible, the direct generation method is essentially hands-on," manual" method that requires as to keep track of all our node numbers as we develop our finite element mesh.

## *III. ANALYZING THERMAL PHENOMENA*

A Thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are:

- The temperature distributions
- The amount of heat lost or gained
- Thermal gradients
- Thermal fluxes.

Thermal simulations play an important role in the design of many engineering applications, including internal combustion engines, turbines, heat exchangers, piping systems, and electronic components. In many cases, engineers follow a thermal analysis with a stress analysis to calculate thermal stresses (that is, stresses caused by thermal expansions or contractions).

### A. Types of Thermal Analysis

ANSYS supports two types of thermal analysis.

a. Steady-state thermal analysis
b. Transient thermal analysis

### B. Steady-State Thermal analysis

The ANSYS Multi-physics, ANSYS Mechanical, ANSYS FLOTRAN, and ANSYS Professional products support steady-state thermal analysis. A steady-state thermal analysis calculates the effects of steady thermal loads on a system or component. Engineer/analysts often perform a steady-state analysis before doing a transient thermal analysis, to help establish initial conditions. A steady-state analysis also can be the last step of a transient thermal analysis; performed after all transient effects have diminished.

We can use steady-state thermal analysis to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by thermal loads that do not vary over time. Such loads include the following:

- Convections
- Radiation
- Heat flow rates
- Heat fluxes (heat flow per unit area)
- Heat generation rates (heat flow per unit volume)
- Constant temperature boundaries

A steady-state thermal analysis may be either linear, with constant material properties; or nonlinear, with material properties that depend on temperature. The Thermal properties of most material do vary with temperature, so the analysis usually is nonlinear. Including radiation effects also makes the analysis nonlinear.

### C. Transient Thermal Analysis

The ANSYS Multi-physics, ANSYS Mechanical, ANSYS Professional, and ANSYS FLOTRAN products support transient thermal analysis. Transient thermal analysis determines temperatures and other thermal quantities that vary over time. Engineers commonly use temperatures that a transient thermal analysis calculates as input to structural analyses for thermal stress evaluations. Many heat transfer applications - heat treatment problems, nozzles, engine blocks, piping systems, pressure vessels, etc. - involve transient thermal analyses.

A transient thermal analysis follows basically the same procedures as a steady-state thermal analysis. The main difference is that most applied loads in a transient analysis are functions of time.

To specify time-dependent loads, we can either use the Function tool to define an equation or function describing the curve or then apply the function as a boundary condition, or you can divide the load-versus-time curve into load steps. For each load step, we need to specify both load values and time values, along with other load step options such as stepped or ramped loads automatic time stepping, etc. we then write each load step to a file and solve all load steps together. To get a better understanding of how load and time stepping works.

### D. Coupled-Field Analysis

A Coupled-field analysis is an analysis that takes into account the interaction (coupling) between two or more disciplines (fields) of engineering. A piezoelectric analysis, for example, handles the interaction between the structural and electric fields: it solves for the voltage distribution due to applied displacements, or vice versa. Other examples of coupled-field analysis are thermal-stress analysis, thermal-electric analysis, and fluid-structure analysis. Some of the applications in which coupled-field analysis may be required are pressure vessels (thermal-stress analysis), fluid flow constrictions (fluid-structure analysis), induction heating (magnetic-thermal analysis), ultrasonic transducers (piezoelectric analysis), magnetic forming (magneto-structural analysis), and micro-electromechanical systems (MEMS).

### E. Problem Definition

A high speed drive system generates more heat through friction, at contact areas, such as the ball screw and nut. The frictional heat induced due to friction is the main source of deformation in a ball screw system, which adversely affects the machining accuracy. Therefore, the thermal deformation of a ball screw is one of the most important objects to consider for high accuracy and high speed machine tools. With this in mind, the thermal behavior of a feed drive system was investigated in order to develop a systematic method of analysis.

**Specification of the ball screw system:**

The specification of the ball screw system is shown in the Table2.

| | |
|---|---|
| Screw shaft length | 1000 mm |
| Screw shaft diameter | 40 mm |
| Nut length | 120 mm |
| Preload | 200 kgf-cm |
| Feed | 20 m/min |
| Stroke length | 600 mm |
| Table load capacity | 350 Kg |

Table2. Specification of the ball screw system.

## *IV. GEOMETRICAL DISCRIPTION*

### A. Creation of Model

The model of a ball screw is created by using solid modeling technique used in ANSYS program. The command used for the creation of the model is by using creation of volume and extrude option**.**

### B. Analysis of the Model

The model is analyzed by the combination of both Thermal and Structural discipline.

Analysis of model includes the following steps.

- PRE-PROCESSING
- ANALYSIS / SOLUTION
- POST-PROCESSING

### C. Pre-Processing

The pre-processing of the finite element analysis involves

- Creation of the model
- Element type
- Material properties
- Meshing the model
- Applying the load &boundary conditions

The ball screw is modeled using solid modeling technique based on the above assumptions.

Element Type:

- Solid 87 elements are chosen for structural analysis.
- Solid 92 elements are chosen for Thermal analysis.

### D. Material properties

The materials used are different composition of Alloy steels.

| Type of alloy steel | Material1 | Material2 |
|---|---|---|
| Composition | 40% Ni | 25% Cr 20%Ni |
| Density ρ(kg/m$^3$) | 8169 | 7865 |
| Specific heat c (J/Kg k) | 461 | 461 |
| Thermal conductivity K(w/ mk) | 10.4 | 12.8 |
| Modulus of elasticity E in (N/ m$^{3)}$ | 2.040e11 | 2.060e11 |
| Poisson's ration, γ | 0.33 | 0.33 |

Table3. Material properties

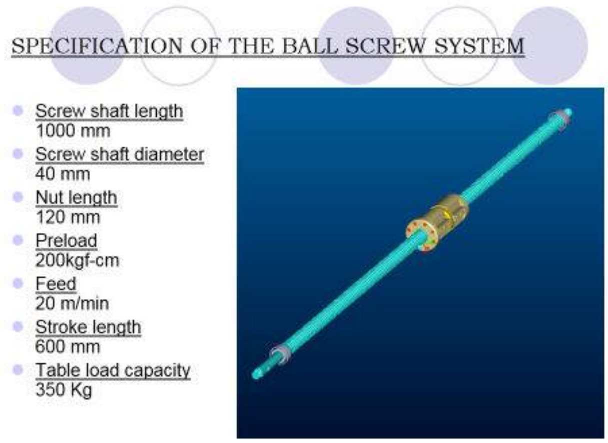
The above properties are taken from the data book
Formula used
Torque, τ = Force x Perpendicular distance (radius) in N-m
Feed, $f$ = πDN/ 1000 in m/min
Frictional heat, $h_f$ = Torque x Rotational speed in W
Heat flux, q = Frictional heat / Surface area in W/m$^2$

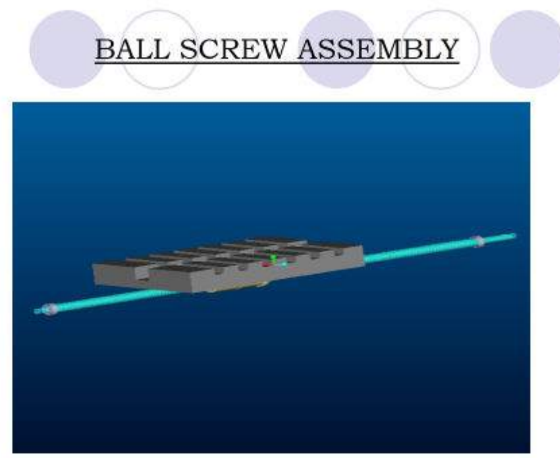
### E. Meshing the model

The meshing of the geometry may be done by either manually or automatically (free mesh). Here the meshing of the model is done by using the option free mesh using solid element of tetrahedron type, the meshed model s are shown in the figures.

### F. Applying the load & boundary condition

1. Machining is not performed, thus the chip effect is not considered.
2. Heat conduction from the motors is replaced by heat fluxes.
3. Heat generated between the sliding surfaces is replaced by heat fluxes directed to the surfaces of the sliding surface elements.
4. The room temperature of the machining center is about 20°C.
5. The machining time is about 8 hours.




### G. Assumptions Made In FEM

- The screw shaft is considered as a solid cylinder.
- Friction heat generation between the moving nut and the screw shaft is uniform at contacting surface and is proportional to contacting time.
- Heat generation at support bearings is also constant per unit area and unit time.
- Convective heat coefficients are always constant during moving.
- Machining is not performed, thus the chip effect is not considered.

## *V. RESULT AND DISCUSSION*

### A. Analysis Of The Model

The model is analyzed by the combination of both Thermal and Structural discipline.

Analysis of model includes the following steps.

- PRE-PROCESSING
- ANALYSIS / SOLUTION
- POST-PROCESSING

**Pre-Processing Steps**

Creation of the model:

The ball screw is modeled using solid modeling technique based on the above assumptions.

Element Type:

- Solid 87 elements are chosen for structural analysis.
- Solid 92 elements are chosen for Thermal analysis

**Material Properties**

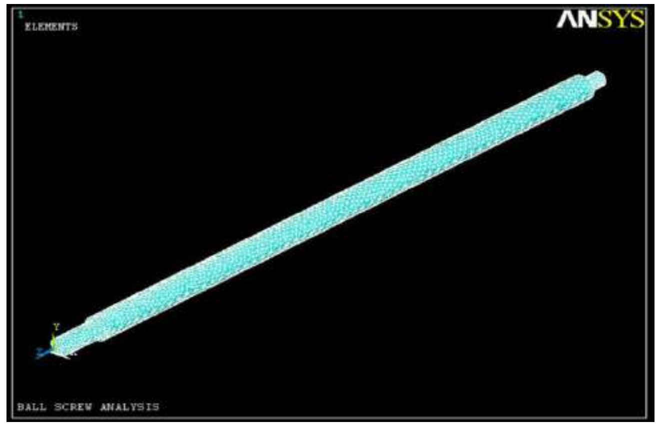
**Room temperature=20°C**

| **Type of alloy steel** | **Material1** | **Material2** |
|---|---|---|
| **Composition** | **40% Ni** | **25% Cr 20%Ni** |
| **Density (kg/m3)** | **8169** | **7865** |
| **Specific heat c (J/Kg k)** | **461** | **461** |
| **Thermal conductivity K (w/mk)** | **10.4** | **12.8** |
| **Modulus of elasticity in (N/ m3)** | **2.040e11** | **2.060e11** |
| **Poisson's ration** | **0.33** | **0.33** |

**Meshing the model**

The meshing of the geometry may be done by either manually or automatically (free mesh). Here the meshing of the model is done by using the option free mesh using solid element of tetrahedron type, the meshed models are shown in thefigures.

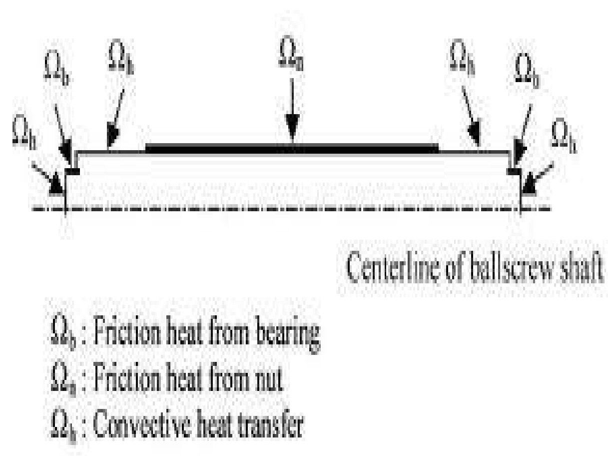
**MESH VIEW**




**Applying the load & boundary condition:**

- Machining is not performed, thus the chip effect is not considered.
- Heat conduction from the motors is replaced by heat fluxes.
- Heat generated between the sliding surfaces is replaced by heat fluxes directed to the surfaces of the sliding surface elements.

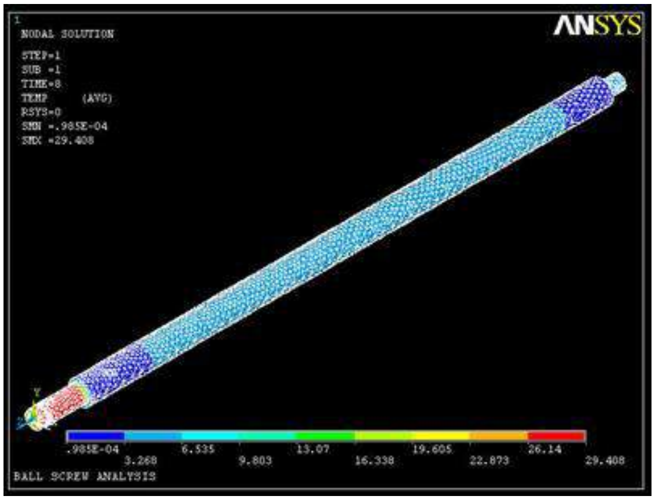
HEAT FLUX VALUEIN W/m$^2$

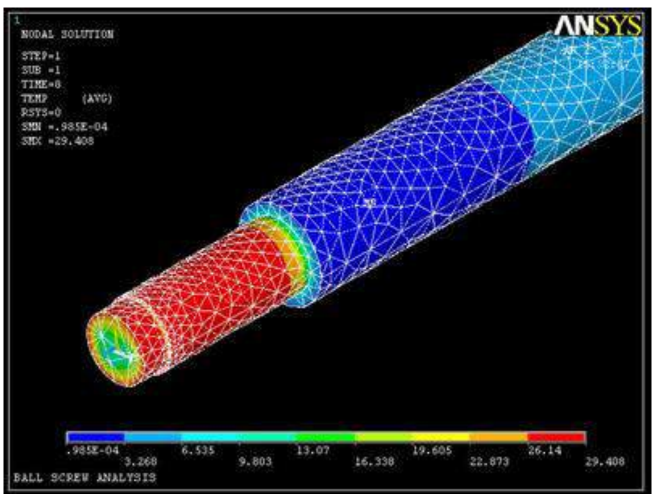



- Motor bearing end
  $7.203*10^3$
- Nut load
  $1.2157*10^4$
- Front bearing end
  $5.052210^4$

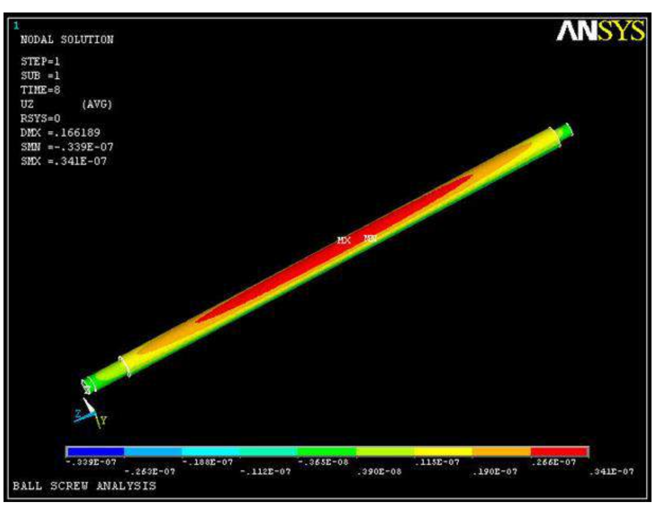
- Free convection
  400

### Material 1: Temperature Distribution

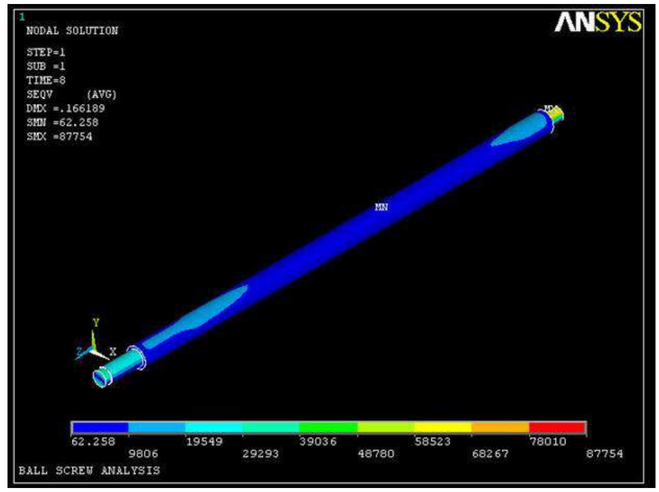


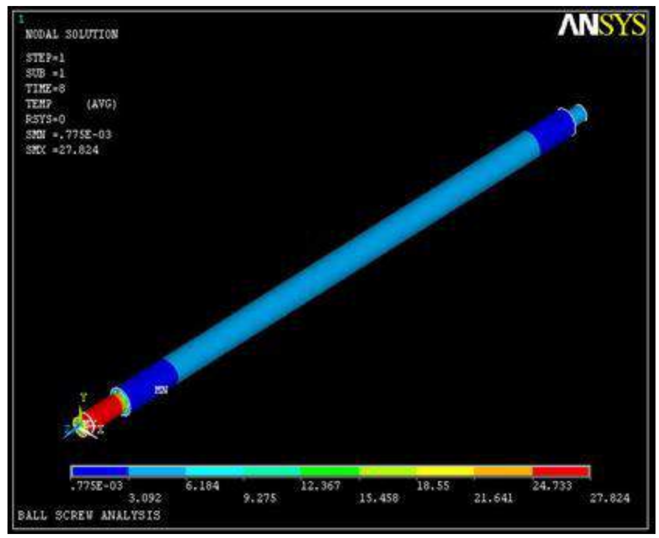



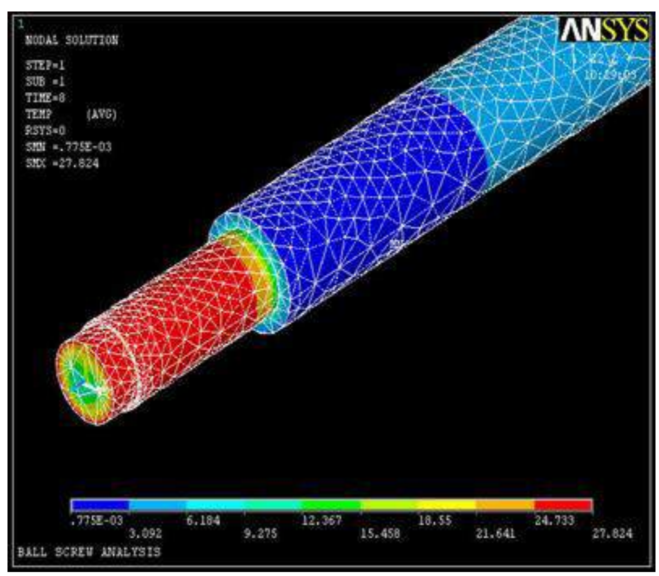

### MATERIAL 1: THERMAL DEFORMATION



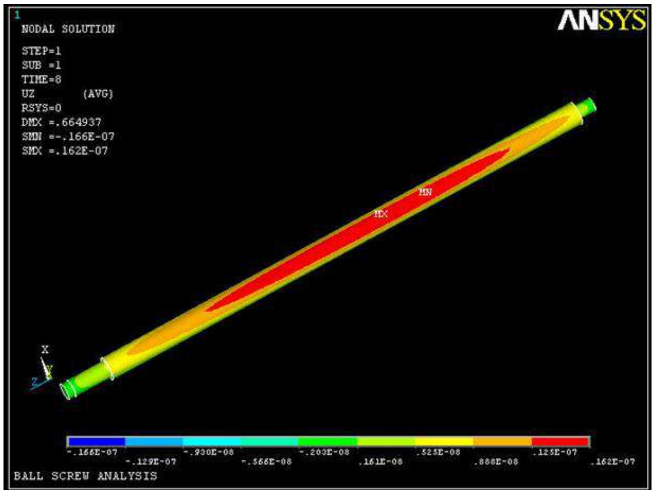

### Material 1: Thermal Stress Distribution



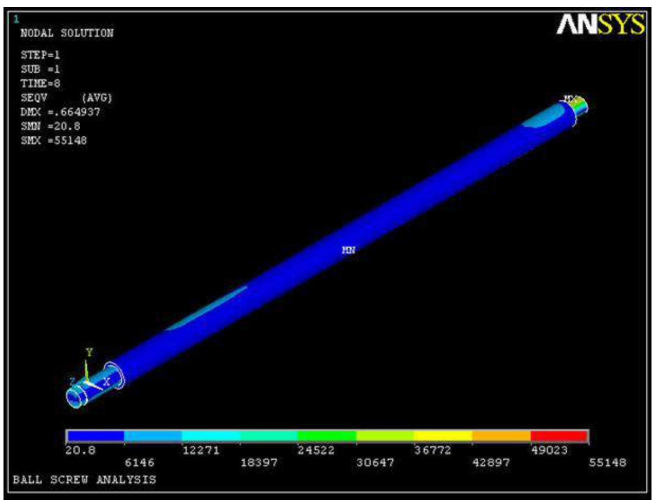



**MATERIAL2: THERMAL DEFORMATION**




**Material 2: Thermal Stress Distribution**




**ANALYSING RESULT VALUES**

| TYPE OF MATERIAL | MATERIAL 1 | MATERIAL 2 |
|---|---|---|
| MAX.TEMP INCREASE IN°C | 29.408 | 27.824 |
| THERMAL ERROR IN m | 0.341e-7 | 0.162e-7 |
| THERMAL STRESS VALUE IN $N/m^2$ | 87754 | 55748 |

- From the analysis the temperature distribution is found to be non- uniform.
- The temperature distribution is high at the driven end than the driving side, due to preload.
- Thermal deformation is found to be high at the centre of the ball screw than at the ends.
- The stress value of the ball screw is found to be within the safe limit as compared to yield stress of the materials.

## *VI. CONCLUSION*

- The Thermal deformation of the ball screw feed drive system have been analyzed for two materials.

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