Modeling the Thread Chasing Process for Improved Product Quality

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ABSTRACT

A simulation model for the thread chasing process, an operation widely used to produce pipe threads, is described. This model focuses on the prediction of the cutting force system, and is based on sub-models for the process geometry, tool-work contact area (chip load), chip load-force relationship, and the structural response of the machining system when acted on by the cutting forces. The model is shown to be capable of predicting the cutting torque, cutting forces, and displacement present in the process. Experimental data obtained from a turning process is used to condition the model to the material of interest. The process model is then verified through physical experiments conducted with the thread chasing process. Discussion is presented on how the model may best be put to use for enhancing the quality of the thread chasing process and its associated products.

INTRODUCTION

Manufacturers are often faced with situations in which the performance/quality of products is heavily dependent on the performance of the machine tools used to produce the products. Machine tool builders, responsible for designing and building many machining processes, have often relied on experience to produce high quality processes. Until recently, however, few techniques existed that permitted machine tool builders to describe, during the design stage, the performance of the machining operations that would ultimately be conducted with the machines. Lack of these design tools has placed machine tool builders in a position where much physical experimentation must be performed, and concomitant expense incurred, in order to produce their machine tools.

To illustrate the above point, consider a manufacturer of pipe thread cutting (or thread chasing) equipment and tooling that recently encountered a problem. The manufacturer had, through years of engineering effort, developed a product line that when used by the customers produced a high quality pipe thread. The problem arose when customers began using the equipment and tooling on a new pipe material. Some of the quality problems produced when using this new material included poorly formed threads, torn threads, and crushed pipe.

The design staff of the manufacturer investigated many solutions to remedy this problem, with each change consuming valuable resources and time, but to no avail. It became clear that although much had been written on thread chasing (1-4)*, and many experimental iterations had been performed, no fundamental understanding of how the process worked had yet been achieved. It was recognized that this lack of understanding inhibited the search for a solution to the thread quality problem.

To develop a better understanding of the thread chasing process, the methodology described in (5,6) was adopted. This approach seeks to model the mechanics of a metal cutting operation. Once a mechanistic model of the process is developed, it is synchronized to the material and cutting fluid in question through the results of carefully planned laboratory experiments. Once the mechanistic model has been conditioned to experimental data and validated through testing, it may be used to experiment with a process. It may be noted that mechanistic models are most often constructed in a form flexible enough so that changes in the tooling, equipment, and processing conditions may be examined. Experimentation with a computer-based simulation model of a process is clearly faster and less expensive than experimenting with the real process. Additionally, it is often the most convenient way to obtain very detailed information about the physical process.

In this paper, a mechanistic model of the thread chasing process will be presented. The experimental work undertaken to condition this model for a given material will then be described. The model will then be compared to data collected from an actual thread chasing process. Some discussion will then be presented on how to best use the model to enhance the quality of the product and process.

MECHANISTIC MODEL OF THE THREAD CHASING PROCESS

Perhaps the most important measures of performance for a machining process are the cutting forces, because they influence the tool life, surface finish, surface error, and process stability. In order to develop a model that may be used to

* Designates references at end of paper.
predict the cutting forces in any machining process, knowledge concerning the effects and interrelationships of the following four components is required:

- The process geometry, i.e., tool and workpiece geometries and relative motions.
- The chip load (tool-work contact area) geometry and cutting edge geometry.
- The relationship between cutting forces and chip load.
- The effect of cutting forces on the relative positions of the tool and work.

When these components are described mathematically and integrated into a framework such as that shown in Fig. 1, they form a model which may be used to predict the cutting forces in a machining process. A model of the form shown in Fig. 1 has been developed for the thread chasing process. The remainder of this section is devoted to a discussion of these aforementioned components, and how they have been incorporated into a simulation model of the thread chasing process.

FIG. 1 Block Diagram of a Cutting Force Prediction Model for a Machining Process

THREAD CHASING PROCESS GEOMETRY
Perhaps the single most important aspect of a thread chasing process which differentiates it from other machining processes are the geometries of the cutting tools (chasers) used in the process. Fig. 2 illustrates a typical chaser geometry. In Fig. 2, the chaser would move from right to left relative to the pipe when cutting. The throat, crests, roots, leading and trailing edges of the teeth define the cutting edge of the chaser, used to remove material from the pipe. Anticipating future experimentation with the cutting edge or tool geometry by design engineers, the cutting edge was characterized mathematically by lines and arcs. This representation would of course facilitate the manipulation of the geometry on a CAD system.

The geometry and coordinate system for a thread chasing operation are illustrated in Fig. 3. As is apparent, a set of 4 chasers is used for the operation, each with a slightly different geometry, matched so as to produce a thread. The chasers are spaced apart by approximately 90°, and their positions are fixed relative to one another. As the process operates, the chasers are rotated around the pipe in a clockwise direction. Owing to the geometry of the chasers, they essentially feed onto the pipe at a speed equal to the pitch of the chasers. Fig. 3 illustrates the fact that the chaser cutting edges are offset from the centerline of the pipe. The effects of this offset are to increase the back rake angle seen by the cutting edge and to reduce the clearance between the flank of the chaser and the pipe. One final point of interest relative to Fig. 3 is that from the figure it is clear that under ideal conditions (i.e., no radial or axial offsets of the chasers from one another) that chaser 1 machines over the surface left by chaser 2, chaser 2 machines over the surface left by chaser 3, and so on.

CHIP LOAD AND CUTTING EDGE GEOMETRY
The most fundamental assumption inherent in the model for cutting force prediction is that the cutting forces are proportional to the contact area (chip load) between the tool and the workpiece, A_c. Therefore, knowledge of the chip load is essential to the prediction of cutting forces. Fig. 4 illustrates the chip load seen by chaser 1 at a specified instant in time as it
machines over the surface left by chaser 2. As can be seen in the figure, the contact area is bounded by the cutting edges of chasers 1 and 2, the outside diameter of the pipe, and the end of the pipe.

(i.e., the distance of the chaser cutting edge from the axis of rotation). The side rake angle would also influence the geometry of the cutting edge, but in the chaser geometries considered in this investigation, they were all seen to be zero. For the case in which the side rake angle is zero, the inclination angle associated with a point on the cutting edge is given by:

\[ i = \tan^{-1}(\tan \alpha_b \cdot \cos d\theta) \]  

where, \( i \) is the inclination angle for a chaser at a specified point on the cutting edge.

One method by which the chip load (shaded area in Fig. 4) may be determined is to decompose the area into small rectangular elements, calculate the areas of the individual elements, and then add them to give the total chip load. This numerical integration may be accomplished by taking small steps of length \( dL \) along the cutting edge, and for each step calculating the elemental chip load. This chip load is the product of the chip width, \( dL \), and the chip thickness, \( CT \). This is illustrated in Fig. 5. Mathematically, this elemental area is given by the equation:

\[ dA = CT \cdot dL \]  

where, \( CT \) is the chip thickness (the length of a normal line segment from the cutting edge to the surface generated by a preceding chaser) and \( dL \) is the incremental step size along the chaser edge.

Attention may now be turned to the orientation/geometry of the cutting edge for a specified point on the edge. The slope of the line segment defined in Fig. 5 is defined by the angle \( d\theta \), where this angle may be interpreted as the side cutting edge or lead angle at that point on the cutting edge. The back rake angle for a chaser is dependent on both the nominal back rake angle (lip angle) and the offset of the chaser cutting edge from the centerline of the pipe. The back rake angle may be calculated with the following equation:

\[ \alpha_b = \alpha_{bn} + \tan^{-1}(A/R) \]  

where, \( \alpha_b \) is the effective back rake angle at the cutting edge for the chaser, \( \alpha_{bn} \) is the nominal back rake (lip) angle for the chaser, \( A \) is the offset of the cutting edge of the chaser from the pipe centerline, and \( R \) is the radius associated with the chaser.

The normal and effective rake angles for a point on a cutting edge are given by:

\[ \alpha_n = \tan^{-1}(\tan \alpha_b \cdot \sin d\theta \cdot \cos i) \]  

\[ \alpha_e = \sin^{-1}(\sin^2 i + \cos^2 i \cdot \alpha_n) \]  

where, \( \alpha_n \) is the normal rake angle at a point on the cutting edge, and \( \alpha_e \) is the effective rake angle at a point on the cutting edge. Knowledge of the effective rake angle is required for the prediction of cutting forces as described in the following section.

**FORCE PREDICTION** - The elemental chip load at a point on the cutting edge, as defined by Eq. (1), produces a force tangent to the pipe, \( dF_e \), referred to as the tangential or cutting force. Additionally, a thrust force, \( dF_t \), is produced which is perpendicular to both \( dF_e \) and the cutting edge at that point. These forces may be related to the elemental chip load by the following equations:

\[ dF_e = K_e \cdot dA \]  

\[ dF_t = K_t \cdot dA \]  

where, \( K_e \) and \( K_t \) are empirical coefficients that depend on \( CT \), \( V \), and \( \alpha_e \), and \( V \) is the cutting speed or tangential velocity of the work material as it moves past the cutting edge.

The elemental thrust force, \( dF_t \), may be resolved into
elemental radial, \( dF_r \), and longitudinal, \( dF_l \), components using the lead angle for that point on the cutting edge, viz.,

\[
dF_r = dF_l \cdot \cos \delta_l
\]

\[
dF_l = dF_l \cdot \sin \delta_l
\]

The elemental forces acting at points along the cutting edge of the jth chaser may be added together to produce the total force acting on the jth chaser at an instant in time.

\[
F_c (j) = \sum_{all \ elements} dF_c
\]

\[
F_r (j) = \sum_{all \ elements} dF_r
\]

\[
F_l (j) = \sum_{all \ elements} dF_l
\]

To find the total force acting on a set of four chasers, or on the pipe, at a given point in time, the cutting forces produced by each chaser may be added together. Since the radial and tangential forces for each chaser act in different directions, to add the forces together they must first be transformed into the external coordinate system. Figure 6 shows the geometry associated with this transformation procedure. Mathematically, the total force exerted on the pipe due to all the chasers at a given point in time is given by Eqs. (13-15).

\[
F_z = \sum_{j=1}^{4} F_l (j)
\]

\[
F_x = \sum_{j=1}^{4} -F_r (j) \cos \theta (j) + F_c (j) \sin \theta (j)
\]

\[
F_y = \sum_{j=1}^{4} -F_r (j) \sin \theta (j) - F_c (j) \cos \theta (j)
\]

where, \( \theta (j) \) is the angular position of the jth chaser.

The equations presented above describe the state of a thread chasing process at a given instant in time (or angular/axial position of the chaser set with respect to the pipe). A rotational history of the cutting forces may be obtained by examining a sequence of these “process snapshots” with the process examinations spaced apart by a small angular change in the position of the chaser set with respect to the pipe. Of course, as the chasers rotate and move onto the pipe the chip load acting on each chaser changes, in turn affecting the radial, longitudinal, and tangential force on each chaser. The procedure described above was implemented on a microcomputer forming a computer based simulation model of the thread chasing process.

**EFFECT OF SYSTEM COMPLIANCE** - In a machining process the forces produced by the process act on the elements of the machining system structure and produce deflections. These deflections impact the position of the cutting tool with respect to the workpiece, and influence the chip load seen by the tool. In a thread chasing machining system, there are a number of relatively flexible elements (work holding devices, pipe wall, etc.) that are sensitive to the cutting forces produced by the process. Most importantly, however, is the fact that the chasers are held in a fixture which is essentially allowed to float freely in the plane perpendicular to the axis of the pipe. This float phenomenon permits the set of four chasers to seek a position in which the vector sum of the radial forces applied to the pipe/chaser set is close to zero. It may be noted that experimental data has shown that pipe sets produced from a system without float (i.e., a rigid system) have poor quality. The role of chaser float in the system becomes even more important given the fact that many of the nominal elemental chip loads are small (chip thickness less than 0.001 inch), meaning that even a minor change in the system deflection can dramatically impact the chip load.

As was illustrated previously in Fig. 1, in order to properly characterize the effect of deflection on chip load and thus, cutting forces, a closed loop model of the cutting process is required, i.e., a deflection feedback mechanism is needed. In the present context, the amount of displacement of a chaser from the pipe impacts the radial position of its cutting edge, or its “effective radius”. Since the model for the chip load uses these effective radii to calculate the tool/work contact area, changes in the effective radii will of course affect the chip load.

If a chaser is deflected away from the pipe due to radial displacements, it will remove less material. This means that approximately 90° later, the next chaser will have to remove extra material. This effect, known as regeneration, means that the chip load is not only a function of current displacement, but also past displacements. Thus, to properly handle the deflection feedback mechanism, knowledge of the
displacement history of the chasers relative to the pipe is needed. The radial displacement history of the chasers relative to the pipe may be obtained if a model for the structural response of the thread chasing machining system is available.

As noted previously, in the thread chasing process, the chaser set is held in such a manner so that it is allowed to move freely in the X-Y plane (see Fig. 7). This fixturing allows the chaser set to seek a position in which the resultant radial force seen by the chaser set (and pipe) is zero. Ordinarily, to characterize such a dynamic response one would consider modeling the system with two one-degree-of-freedom system models (one model each for the X and Y directions), i.e., a mass, spring, and dashpot for each direction. Unfortunately, in this case the characterization of the float phenomenon by this method was not possible. Since the thread chasing process is typically performed with a rotational speed that is small relative to other machining processes (e.g., 15 rev/min), and the response time associated with the chaser movement relative to the pipe is quite fast, an extremely small angular/time simulation step would be required to keep the simulation model stable numerically. This would lead to prohibitively long simulation times. Therefore, to characterize the float mechanism, an iterative scheme was devised to balance the forces/displacements at each angular position so that the resultant radial forces would be zero.

![Fig. 7 Chaser Fixturing and Coordinate System for Chaser Float Calculation](image)

To illustrate the float mechanism scheme that was implemented in the process simulation model, consider again Fig. 7. In Fig. 7 it is seen that chasers 2 and 4 produce radial forces that oppose one another in the X' direction. Likewise, it may be seen that chasers 1 and 3 produce forces that oppose one another in the Y' direction. To characterize the effect of chaser float consider the resultant force (F_R - F_T) in the X' direction. If this force is positive, i.e., the force due to chaser 4 is larger than that due to chaser 2, motion of the pipe relative to the chaser set will be in the positive X' direction (the chaser set will move in the negative X' direction). Motion will continue in the X' direction until the resultant force due to chasers 2 and 4 is zero, i.e., a force balance is achieved. A similar balance will be achieved in the Y' direction between chasers 1 and 3.

To achieve a balance between the forces acting on the chaser set within the model, several iterations are performed at every angular position. For a given angular position, the displacements of the chaser set are initialized to be zero at the start of the first iteration. For each iteration, the resultant forces are computed. Using the magnitude and sign of the resultant forces, new displacements are selected so as to produce resultant forces at the next iteration that are closer to zero. The force balancing, or iterating, is continued until the resultant forces are sufficiently close to zero.

**MODEL CONDITIONING AND VERIFICATION**

The model developed previously is capable of predicting the cutting forces in the thread chasing process, and in addition, can predict the displacements due to the float phenomenon. Of course to make these predictions, the process model must be conditioned to the work material of interest. Conditioning or synchronizing the process model essentially means that values of K_c and K_t must be obtained. Once the process model has been conditioned, model predictions may be compared with the corresponding measures from the actual process to assess the ability of the model to accurately simulate the process. This section describes both of these experimental procedures, conditioning and verifying the model.

**MODEL CONDITIONING** - As noted previously, the cutting forces may be assumed to be proportional to the chip load through empirical functions for K_c and K_t. These empirical models may be developed by running a small set of conditioning tests, often performed using a turning process. These experiments should span the range of cutting conditions that are expected to be present during the actual conduct of the chasing process. Since the empirical models to be developed are dependent on the chip thickness, cutting speed, and effective rake angle, cutting conditions should be selected that produce a wide range for these variables. The rationale for wanting wide experimental ranges for these variables (chip thickness, cutting speed, and effective rake angle) is that the resulting empirical models are then reliable across a wider range of the variables of interest.

Daring turning experiments, it is most common to measure the tangential (F_tan), longitudinal (F_lon), and radial (F_rad) cutting forces. Based on the measured cutting forces, feed (f), and depth of cut (d), values for K_c and K_t for that test may be calculated:

\[
K_c = \frac{F_{tan}}{fd} \quad (16)
\]

\[
K_t = \frac{\sqrt{F_{rad}^2 + F_{lon}^2}}{fd} \quad (17)
\]
If a number of turning tests are performed, and \( K_c \) and \( K_t \) values are determined for varying levels of chip thickness, effective rake angle, and cutting speed, the following empirical equations may be fit to the data:

\[
\ln (K_c) = A_0 + A_1 \ln (CT) + A_2 \alpha_e + A_3 \ln (V) \quad (18)
\]

\[
\ln (K_t) = B_0 + B_1 \ln (CT) + B_2 \alpha_e + B_3 \ln (V) \quad (19)
\]

Once these equations have been fit to the data, they may be used for prediction purposes, i.e., given values for the chip thickness, effective rake angle, and cutting speed, values for \( K_c \) and \( K_t \) may be calculated.

A set of 60 turning tests were performed by the staff of the Institute of Advanced Manufacturing Sciences (IAMS) using the variable settings given in Table 1. For each of the ten tool geometries the six possible combinations of the speed and feed were examined. Since the nose of the cutting tool was inside the pipe for all the tests, the depth of cut was 0.133 inch (the wall thickness) for all the tests. For each test, the cutting forces \( F_{\text{tan}}, F_{\text{lon}} \), and \( F_{\text{rad}} \) were measured and, using Eqs. (16) and (17), values for \( K_c \) and \( K_t \) calculated. To fit Eqs. (18) and (19) to the data, values of cutting speed (\( V \)), effective rake angle (\( \alpha_e \)), and chip thickness (\( CT = \text{feed} \times \cos(\text{lead angle}) \)) were also calculated for each test.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Variable Settings for Model Conditioning Experiments</th>
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**Tooling**

High speed steel tooling. All relief angles: 5 deg. The Lead, Back Rake, Side Rake, and End Cutting Edge angles are given in parentheses.

- Tool 1 (0, 0, 0, 5)
- Tool 2 (0, 0, 5, 5)
- Tool 3 (0, 5, 0, 5)
- Tool 4 (0, 5, 5, 5)
- Tool 5 (0, 0, 20, 5)
- Tool 6 (45, 0, 0, 5)
- Tool 7 (45, 0, 5, 5)
- Tool 8 (45, 5, 0, 5)
- Tool 9 (45, 5, 5, 5)
- Tool 10 (45, 0, 20, 5)

**Work Material**

U.S. "black" pipe, nominal dimensions: 1.315 in. OD and 0.133 in. wall thickness

**Cutting Conditions**

Spindle speed: 20 and 30 rev./min.
Feed: 0.0017, 0.0038, and 0.0084 in./rev

Based on the levels for the independent variables (cutting speed, effective rake angle, and chip thickness) and the responses \( K_c \) and \( K_t \) for each test, Eqs. (18) and (19) were fit to the data, and the resulting equations are shown below:

\[
\ln (K_c) = 11.3644 - 0.3319 \ln (CT) - 1.764 \alpha_e + 0.033 \ln (V) \quad (20)
\]

\[
\ln (K_t) = 10.6555 - 0.3905 \ln (CT) - 3.572 \alpha_e + 0.012 \ln (V)
\]

With the empirical relationships of Eqs. (20) and (21) available, the thread chasing process model is then conditioned to the work material of interest. Attention may now be turned to verification of the process simulation model.

**MODEL VERIFICATION**

To assess the ability of the thread chasing process model to accurately predict the performance of the process, a specific thread chasing scenario was selected. It was decided to predict and measure the performance of the process when producing a 1.25 inch ANSI standard tapered pipe thread on U.S. "black" pipe. Since this type of thread could, in principle, be produced by many different chaser geometries, the chaser geometries currently being manufactured were selected for study. For these conditions, the process was simulated using the thread chasing process model, and such measures as the cutting torque, forces on each chaser, and displacement of the chaser set relative to the pipe were recorded. To measure the performance of the actual process, two experimental setups were developed; one by the thread chasing equipment manufacturer, and one by the staff of IAMS. For both of these test rigs, the cutting torque was recorded for the same conditions as those for the process simulation.

Figure 8 displays the predicted cutting torque for the operation described above. From the figure, the effect of the chasers moving onto the pipe is clearly evident, with the chasers starting to cut at approximately 200 degrees. As the chasers move onto the pipe the torque increases nearly linearly. By the end of the ninth revolution all portions of the cutting edges for all the chasers are in contact with the pipe. Thus, for angles greater than 3240 degrees the cutting forces and cutting torque are at their steady state values. The torque appears to reach a maximum level at its steady state value of approximately 180 ft. lb.

![Figure 8: Predicted Cutting Torque from Thread Chasing Simulation Model](image)

Figure 9 shows the tangential force acting on chaser number 1. The appearance of this curve is similar to that of the predicted cutting torque curve. The force reaches a maximum...
of approximately 570 lb. when it reaches steady state. Also evident from the figure is an apparent discontinuity near an angle of 1000 degrees. This was reasoned to be due to the fact that the chaser geometry where the throat intersects the teeth (described by the thread form angle, taper angle, etc.) can be very different from chaser to chaser. Since at approximately 1000 degrees this intersection is coming into contact with the work, it is apparent that the geometrical difference between chasers also dramatically impacts the chip load/forces.

![Graph of Force vs. Angle](image)

**Fig. 9** Predicted Tangential Force on Chaser 1 from Thread Chasing Simulation Model

The displacement of the pipe relative to the chaser set in the X- and Y- directions is shown in Fig. 10. From the figure it is clear that the chaser float has a tremendous impact on the process. Approximately one revolution after cutting is initiated, the chaser set is displaced from the pipe in the X-direction by over 0.004 inch. At the same angular position, the displacement in the Y-direction is small. Since at this angular position chasers 1 and 3 lie in the X-direction, the fact that this displacement is large is suggesting that the nominal difference between the chip loads carried by chasers 1 and 3 is also large, and the float phenomenon compensates for it. Approximately 90 degrees after the displacement is largest in the X-direction, the displacement in the Y direction becomes quite significant. For this angular position, now chasers 1 and 3 lie in the Y-direction, and the effect is as described previously. As the chasers move further onto the pipe, the amount of displacement generally decreases, and at steady state is within ±0.0002 inch.

As noted previously, the conditions simulated by the thread chasing model were also examined experimentally via two test rigs. The cutting torque was measured as a function of time in both cases, and these experimental results are displayed in Fig. 11. This figure may be compared to Fig. 8, which displays the model predicted cutting torque. In Fig. 11, since the speed used for the tests was 30 rev/min, approximately nine cutter rotations are displayed. The shape of the measured and predicted torque curves are similar, however, the predicted maximum torque is somewhat greater than the measured torque. This difference may be due to inaccuracy in the empirical equations for $K_c$ and $K_r$, or due to deviations of the manufactured chaser geometry used in the physical experiments from that specified by the blueprint. With all things considered, it was concluded that the thread chasing model was reasonably verified by the experimental data.

![Graph of Displacement vs. Angle](image)

**Fig. 10** Model Predicted Displacements of the Pipe Relative to the Chaser Set

![Graph of Torque vs. Time](image)

**Fig. 11** Measured Cutting Torque for the Two Experimental Test Rigs

**POTENTIAL MODEL USE**

With a model for the thread chasing process now developed and verified, attention may now be turned to use of the model. As has been seen, the model may be used to predict the cutting torque. This ability would assist in the selection of motors to be used in the thread chasing process. Since the cutting forces are also predicted by the model, this force information may be used to design the fixturing and workholding for the process.

Another potential use of the model is to extract information from the process that might be difficult, if not
impossible, to obtain experimentally. To illustrate this use, consider again the displacement data of Fig. 10. By carefully interpreting this data, it was revealed that an imbalance existed between the nominal chip load associated with chasers 1 and 3. Such information would obviously be useful from a chaser geometry design standpoint.

Perhaps the best way to use a process model is to experiment with it so as to develop an understanding for how the various design variables influence the resulting product/process performance. Experimentation with a computer-based simulation model of a process is most often faster and less expensive than experimenting with the real process. Another advantage of experimenting with a process model is that factors that would be uncontrollable in the physical environment, often termed noise factors, can be carefully studied in the model environment. One classical way of studying both design and noise variables in an experiment is with an inner/outer array (7-9).

To illustrate process model study via an inner/outer array, consider the two design variables: throat angle and lip (back rake) angle, and the two noise variables: chaser 1 radius and chaser 1 axial position. The two noise variables in this case are associated with the actual position of chaser 1 at the start of the operation. Of course, ideally all the chasers have the same radial and axial positions, but due to manufacturing variation and the assembly of the chasers into the fixture (see Fig. 7), there will be some deviation from these nominal positions. Figure 11 shows the inner/outer array experimental design associated with these variables.

![Graphical Representation of Inner/Outer Array](image)

Fig. 11 Graphical Representation of Inner/Outer Array

To conduct the experiment associated with Fig. 11 requires 16 tests, one for each small circle in the corner of the squares in the outer array. From such a two-level factorial experiment a great deal of information could be extracted. The singular and joint effects of all the variables under study could be calculated for any response of interest. Using these effects, one could identify levels for the design and noise variables that give improved values for the response of interest.

Unfortunately, selecting values for the noise variables that produce a good level for the response of interest is somewhat meaningless since in reality we typically have little control over the noise variables. Rather, it is suggested that for each combination of the design variables in the inner array (large circles in Fig. 11) the tests associated with the different combinations of the noise variables be treated as replications. Based on these replications, a mean and standard deviation can be calculated for each combination of the design variables. The singular and joint effects of the design variables on the mean response of interest could then be calculated. Additionally, the singular and joint effects of the design variables on the standard deviation could be calculated. Using these mean response and standard deviation effects, levels for the design variables can be selected that not only produce a good response on the average, but also a response with small variability. In other words, levels for the design variables can be selected that produce a response that is robust to the effects of the noise variables, in this case the radial/axial position of chaser 1. Clearly, this approach for selecting design variable levels that mitigate the deleterious effect of variation on performance represents a powerful tool for producing quality in products/processes.

**SUMMARY**

In this paper a simulation model for the thread chasing process has been described. The model considers the complex geometry of the chasers and kinematics of the thread chasing process. The process model has been seen to be composed of sub-models for the tool-work contact area (chip load), chip load-force relationship, and the structural response of the machining system when acted on by the cutting forces. The model is shown to be capable of predicting the cutting torque, cutting forces, and displacement present in the process. Key features of the model include:

- The model is mechanistic in nature - it attempts to describe the mechanics of the process.
- The model constructs a CAD-type representation of the chaser (cutting tools) based on the parametric definition of the chaser geometry.
- Some noise variables such as chaser radius and chaser axial position are characterized by the model.
- Although mechanistic in form, the model must be conditioned or synchronized to the work material of interest through experimental data. This data is often conveniently obtained from a turning process.
- The model describes the float of the set of chasers about the pipe, float being a phenomenon in which the chasers seek a position that makes the resultant force zero.

As suggested above, the process model must be conditioned to the work material of interest via experimental data. Such data was obtained through a set of 60 turning tests. The model was then verified through physical experimentation conducted on two test rigs performing the thread chasing process. Specifically, a chaser geometry was selected, and the process model was used to predict the cutting torque. The
cutting torque was then measured for chasing operations (performed under like conditions) done on the two test rigs. The shapes of the measured and model predicted torque curves were seen to be similar, and the peak torque was also close.

The best use of a process model such as the one described herein may be by viewing it as an experimental tool for process study. Experimentation with a process model is often faster and less expensive than experimenting with the real process, and also may reveal more detail about the process. One type of experimental design that may be used to structure such an experimental study is an inner/outer array, a design that considers both design and noise variables. The consideration of noise variables is an important feature of this design, as it is the variation in the noise variables that produces undesirable variation in the response. One course of action when considering the results of an inner/outer array is to select levels for the design variables that minimize the transmitted variation of the noise variables into the response. This philosophy of robust design permits a designer to select variable settings that produce consistent performance, i.e., high quality.

REFERENCES