Machining Processes

Model-Based Planning and Diagnostics

Laboratory Manual

William J. Endres, Ph.D.
Associate Professor
Department of Mechanical Engineering – Engineering Mechanics
Michigan Technological University
Houghton, Michigan

President
Endres Machining Innovations, LLC

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Appendix D
Laboratory Manual

D.1 Laboratory Safety

Safe use of laboratory facilities and equipment is a primary concern and responsibility of <u>all</u> users, instructors and supervisors. During your first day in the laboratory, locate all the emergency and safety equipment that is provided. This may include first aid kit(s), fire alarm(s), fire blanket(s), fire extinguisher(s), fire hose(s), emergency exit(s) and emergency phone(s). All individuals occupying a laboratory are expected to follow all the safety rules and procedures listed below.

General safety rules include:

1. Be alert, safety minded and ready to point out any unsafe conditions you observe in the laboratory.
2. Safety glasses are to be worn at all times.
3. Do not power-up active (electric, hydraulic, pneumatic, chemical, etc.) equipment unless there is someone else in the area to assist in the case of an emergency. This does not include passive equipment, such as optical microscopes, cameras, tooling preparation, data acquisition, and the like.
4. Never carry out unauthorized, unplanned or unscheduled experiments. Proper supervision is required at all times.
5. Keep the work area and laboratory clean and free of clutter and trip hazards.
6. Report all tools and equipment that appear to be damaged, broken or unsafe.
7. Report all incidents and/or injuries to the supervisor of the activity. An accident report must be filled out for all accidents within 24 hours. Forms are available in the Department office.

Due to hazards that result from the presence of oils, cutting fluid, chips, dirt, chemicals and heavy objects, additional rules include:

8. Food or beverages are <u>not</u> permitted in the laboratory at any time.
9. Closed shoes must be worn when working in the laboratory (i.e., open shoes and sandals are <u>not</u> permitted).
10. Full-length pants must be worn when working in the laboratory (shorts, skirts, skorts, dresses or pants that are less than full length are <u>not</u> permitted).
11. Use extreme care when handling chips as they can be razor sharp on their edges.

Of particular concern when working with heavy manufacturing equipment is an awareness of the velocities of the machines and the forces occurring in the processes, and being cautious of the related dangers. Keep in mind that if a process can cut metal, it can handily cut flesh and bone. If a process can form metal, it can heartily crush flesh and bone. And if a process can melt metal, it can heartily burn flesh and bone; many tools get very hot though they may not appear to be (e.g., not red-hot) — they too can burn flesh. Finally, rotating equipment presents hazards as a result of the high-speed rotation alone, which introduces additional rules; they include:

1. Loose or flowing garments (neckties, scarves, etc.) that may get caught in a machine must be restrained or (preferably) removed.
2. Loose or flowing hair that may get caught in a machine must be restrained.
3. Jewelry (rings, watches, necklaces and hanging/dangling earrings) must be removed.
4. Long shirtsleeves must be rolled up to above the elbow.
5. Never leave a chuck key in a chuck.
6. Never attempt to clear chips entangles with a rotating part or tool during operation.

While one need not be afraid of the equipment if proper caution is taken, one should respect the seriousness of safety around manufacturing equipment.

D.2 Data, Analysis and Reporting

All data analyses in this laboratory manual can be done using spreadsheet software, such as Microsoft Excel®. While the first assignment requires one to independently formulate the analysis approach, all other assignments provide step-by-step guidance through a well-organized data analysis. Each data analysis is configured to support the answering of the questions posed, answers to which make up that majority of the report.

D.2.1 Units of Measure

English units are used in some of the *Data Records* provided in each assignment. This is done for the sake of convenience. For instance, English units are used for test variables that are settable only in English units, such as machine settings like feed rate, and for inputs that are more readily measurable in English units, such as cutting speed. Another use of English units is for responses that may be more readily measurable in English units, such as chip dimensions. Despite these strategic uses of English units, all analysis should ultimately be conducted in SI units.

D.2.2 Data Organization

Before proceeding with any analysis, it is useful to organize the measured data for all tests and repetitions. For various reasons of convenience, if not simply to break up the experimental plan into pieces that are manageable for an individual team, the full experimental plan is often broken into *test blocks*. Within a test block, a subset of the variables are varied while the other "blocked" variables are held constant. Each test block then involves a different combination of the blocked variables. Each test block, and each of its repetitions, is referred to as a *test set*.

Data from each test set can be organized in a *Test-Set Data* worksheet; there would be one worksheet for each test set. The Test-Set Data worksheet(s) should be similar in form to the Data Record, but should have all values converted to SI units. Next, the measured data should be averaged across repetitions, referred to as *repetition-averaged* data, in a *Test-Block Data* worksheet; there would be one worksheet for each test block. Averages can be conveniently computed via references to the Test-Set Data worksheets corresponding to the respective test block. The test-set and test-block worksheets provide quick access to data for each test set and the repetition-averaged data for each test block. Each Test-Block Data worksheet should be identical in form to the Test-Set Data worksheets, with all non-blocked variables being the same and all measured data being averaged across all repetitions. If there is no repetition, then the Test-Set Data worksheets serve the same purpose as the Test-Block Data worksheets, meaning the latter can be ignored.

When creating a data table, it is good practice to use two rows above the data rows as column headings that include both the name of the data in that column (first heading row) and its units (second heading row). It is also good practice to include a merged cell across the top of each data table to indicate what the data is from or is for.

D.2.3 Analysis Organization

Given the organization of the data as described above, each analysis can then be performed in a separate worksheet. Each analysis table should be built up via references to the data sheets. More often the references will be to the Test-Block Data worksheets, though sometimes reference to the Test-Set Data worksheets will be in order. In all but the first assignment, spreadsheet workbook templates are provided for the Test-Set Data, Test-Block Data and analyses. In the analysis worksheets, some of the columns require equations to be entered while other columns are intact as provided. In addition, a duplicate of each analysis table is provided with sample results for use in checking that entered equations are correct.

D.2.4 Reports

The report should begin with an *Introduction* section that provides a brief description of the experiment that is written in the student's own words. The introduction should describe the purpose of the experiment, the equipment and the procedure. The second section, *Data Analysis*, should include specific answers to the questions asked in the assignment, with references made to the supporting data analyses (e.g., tables or plots) and documentation of any equations used. The origin of the equations should be noted — either from class notes, example problems, the assignment, or derived. In the case of derived equations, the derivation steps should be shown, details of which are appropriate for an appendix. The Data Analysis section should be broken down into sub-sections in the same way that the "Data Analysis and Questions" section is posed in the assignment. The final section is the *Conclusions* section, which should be presented as bulleted list. Note that the *Conclusions* section is not a summary of the report. The Conclusion section must present only conclusive findings and often takes substantial thought to isolate conclusions from summary items.

The report should be neatly presented and as brief as possible; each assignment will specify the maximum number of pages for its report. Figures and tables, which should be placed at the end of the text portion, do not count in the specified page limit. An appendix with further details may be included. While an appendix is not necessary, since the report is submitted for grading, an appendix is typically a good addition to show details of the work done to facilitate grading and the possibility of partial credit. If an appendix is included, the remainder of the report must stand alone without the appendix; the appendix is there only for further information for the interested reader. Formatting is to be double spaced, 12-point font and one-inch margins.

D.3 Force Measurement

Forces and torques are measured using a dynamometer. Dynamometers can be designed to measure forces and/or torques in one, two or three directions. In machining applications, it is typical to use a three-component force dynamometer, or in the case of drilling, a four-component dynamometer is often used to measure the three forces and the torque about the drill axis. There are two basic types of dynamometers — strain-gage and piezoelectric. Either is sufficient for the testing conducted here. Each is described below with a focus on how it provides the force measurement as an analog voltage signal that can be recorded on a data acquisition system.

D.3.1 Strain-Gage Dynamometers

A strain-gage dynamometer is basically a beam that, when bent or axially strained under load, provides a strain that is measured with a strain gage. A strain gage is a deformation sensitive electrical resistor network. One or more strain gages are glued to the beam. A known input electrical voltage is applied across the strain gauge while the change in electrical current passing through the strain gage is measures. This electrical current is proportional to the change in resistance, which is related to the elongation of the resistor network and hence the strain of the beam. The current is amplified and output as a voltage signal. Through calibration with known loads applied, the measured voltage is scaled to a measured force.

The actual layout and design of general-purpose commercial strain-gage dynamometers is more sophisticated than the above description, but they all work on this same basic principle. It is not very difficult, in fact, to build a dedicated/specialty strain-gage system to measure forces by adhering strain gages to a tool shank and detecting its elastic deformation strains.

D.3.2 Piezoelectric Dynamometers

A piezoelectric dynamometer consists of stacks of piezoelectric crystals oriented in the directions of the forces to be measured (and offset from a reference axis for torque measurement about that axis). The piezoelectric stacks can be subjected only to axial compressive deflection; therefore, to measure tensile loads, they are installed under compressive preload so that the net loading never becomes tensile. When a load is applied and causes deformation in a piezoelectric stack, an electrical charge is generated. The generated charge is then converted to a voltage by a charge amplifier. The voltage signals can then be scaled to force levels knowing the sensitivity of the dynamometer, in Coulombs per force unit, as determined via calibration using known forces.

Since piezoelectric crystals are very stiff, force measurement can be achieved while introducing negligibly small deformations. As a result, piezoelectric dynamometers are very stiff compared to strain-gage based dynamometers. Of course, piezoelectric dynameters are also more expensive as are their associated electronics (charge amplifier).

D.4 Testing on a Manual Engine Lathe

D.4.1 Lathe Operation

D.4.2 Test Execution

One should target about 50 revolutions of data for each force measurement test. The corresponding feed-distance traveled in inches is (50 [rev])(feed [in/rev]). At higher spindle speeds, this will obviously take less time. The corresponding time of each cut, in seconds, is (60 [sec/min])(50 [rev])/(V [ft/min]/0.25π [ft/rev]). A good practice is to calculate the feed-distance each test will require and, prior to each tests, mark that approximate distance on the workpiece with a permanent marker so that the machine operator can easily see when the tool should be stopped at the end of the test. Overshooting that point is not a critical flaw, although it does result in more rapid consumption of workpiece material. On the other hand, stopping the test short could result in an insufficiently short interval of data over which an average must be computed. Therefore, it is better toe err on the side of running too long than too short.

The data acquisition operator is responsible for starting to record data when the feed is engaged and for not stopping acquisition until after the feed is disengaged. If the data acquisition teammate cannot see the feed control on the machine, the machine controller can give a verbal or visual signal when the feed is engaged. However, verbal signals are less preferred since the level of noise in the lab, in particular due to the machine, can drown out verbal cues.

D.5 Design of Experiments

D.5.1 Elementary Design of Experiments

D.5.2 DOE-Based Model Development

D.5.3 Experiment Implementation

Experimental data exhibits noise as a natural phenomenon. The basic approach to reducing the effect of noise is to acquire more data. This can be done by defining more levels of each variable, and/or through repetition — running each test (each combination of variables) multiple times. Repetition is important since it allows an averaging of multiple measurements at each combination of variables. Since experimental noise has a zero expected (mean) value, having many repetitions would effectively average the nose component to its expected value of zero. It is typically not practical to run that many repetitions, however having even three measurements can provide, in addition to averaging of noise, the identification of an erratic measurement. For instance, if one of the three is way measurements differs greatly from the other two that are similar, it is safe to say that the first measurement cited occurred under some unusual, uncontrolled circumstance.

Another important consideration is the test order. Experimental designs are usually presented in standard order, which systematically toggles the level of one variable at a time as the rows of the table are generated. However, running the tests in this order can introduce a trend with a variable that is really a trend with time. That is, a time-dependent trend, such as tool wear, could appear as a trend with respect to a variable that is increasing steadily throughout the standard order. Therefore, it is important to randomize the test order so that any time-dependent trend gets randomly applied across the variables and will than show up as noise. Furthermore, it is advantageous if possible to randomize tests differently in each repetition.

Another experiment implementation strategy is blocking. Blocking is used in cases where a one or more variables are more difficult to change compared to ease in changing the other variables, in which case randomizing the one or more variables into the full set of tests is not practical. For example, while changing spindle speed and feed rate is easy through the machine controls, changing a rake angle requires changing the tool, which is more cumbersome. Therefore, the experimental design might be blocked on rake angle, so that for each rake angle all combinations of feed, speed, etc. would be randomized, and then each randomized set of tests would be re-run for each level of rake angle. As another example, changing from a large depth of cut to a small one is not cumbersome; however, manual lathes sometimes exhibit significant backlash in their radial cross-slides, which requires extra care when backing out from a larger depth of cut to a smaller one. On the other hand, when changing from a small depth of cut to a larger one, even more special care is needed due to the need to radially plunging into the workpiece to achieve the increase in depth of cut. Therefore, one must balance the theoretical rigor of complete randomization with the practical convenience and reduced variability that come with blocking. An additional use of blocking in these assignments is to break up the experimental designs so that each team can do a portion of the entire design rather than the entire design.

D.6 Linear Regression in Excel

D.7 Assignment 1 — Orthogonal Cutting of Clay

This assignment involves an experiment in which one visually observes the process of orthogonal cutting followed by measurement of the chips formed. To allow visual observation and physical interaction with the tool and chips both after and during the operation, clay is cut at a magnified scale. The objectives of this assignment are

- to observe the effect of rake angle on chip formation,
- to observe the effect of clay firmness (stress-strain properties) on chip formation,
- to make basic chip geometry measurements, and
- to contrive an analysis approach and write a short report summarizing observations, in particular the effects of rake angle and material.

The report for this assignment should be no more than two (2) pages of text given the report organization and formatting guidelines presented in the Data, Analysis and Reporting section.

D.7.1 The Experiment

D.7.1.1 Apparatus

The apparatus consists of a a scaled-up cutting tooth that is affixed to a milling machine by clamping its protruding shank into the machine's chuck. Putting the machine in low gear and/or applying its spindle brake is sufficient to keep the tool from rotating about the machine's spindle axis. The cutting tooth has a straight-edged portion that is used for this experiment with the radiused corners to be used in a later experiment. Different rake angles are achieved using a set of scaled-up cutting teeth fabricated for specific rake angles of interest.

The workpiece is a block of modeling clay, or more precisely, plasteline (plas-tuh-lēn). This particular clay is also sulfur-free, which allows it to be heated without burning. Therefore, it can be melted allowing the raw blocks (and recycled scraps from past tests) to be poured into a mold to achieve the desired sample geometry. The mold creates a block of clay that is integrated with a clamping block. The clamping block has twelve (12) hex-head cap screws protruding upward one inch from its top surface. These screws, upon solidification of the clay around them, serve to hold the clay sample from sliding and lifting off of the clamping block. The clamping block is held in the vise below the cutting tooth. For each successive cut, to achieve the specified uncut chip thickness, the table of the milling machine is adjusted vertically.

D.7.1.2 Tests

Tests are conducted on a single sample for all combinations of two levels of uncut chip thickness and two levels of rake angle. These tests are also to be conducted on a second sample of harder clay. The uncut chip thickness levels are $\frac{1}{8}$ and $\frac{1}{4}$ inch. The rake angles are zero and +15°. At the start of a new block, it should be positioned in the vertical direction so that a layer of material can be removed as an initial "clean-up" cut, which is often used to create a known, consistent, and flat reference surface before performing any tests from which data are to be collected.

D.7.1.3 Measurements

The *Data Record* at the end provides spaces for entering measurements. After each test, measure and record the thickness, length and width of the chip using a scale for the length and width and a micrometer for the thickness. Also, make note of any visual observations related to its flow during the cut and the surface created. Note any difficulties encountered in making the chip measurements or performing the cut.

D.7.2 Data Analysis and Questions

D.7.2.1 Rake Angle Effects

Analysis

To support the answering of the questions below, analyze the data in whatever way deemed appropriate, e.g., plots, calculation of changes in data relative to changes in input.

Questions

1. Considering only the soft clay tests, how, if at all, does the rake angle affect the dimensions of the chip? Make your assessment based on ratios of the "cut" values to their respective "uncut values" ($r_h = h/h_c$, $r_l = l_c/l$, and $r_w = w/w_c$), e.g., chip thickness as a ratio to uncut chip thickness (chip thickness ratio r_h).
2. Was any difference in resistance (difficulty in turning the hand crank) observed between the two rake angles? Explain why this observation does or does not make sense.

D.7.2.2 Clay Stiffness Effects

Analysis

To support the answering of the questions below, analyze the data in whatever way deemed appropriate, e.g., plots, calculation of changes in data relative to changes in input. It is wise to recycle any analysis tables from above for analyses here that have the same "form" despite a change in the input variable of interest.

Questions

1. Considering only the zero rake angle tests, how, if at all, does the stiffness of the clay affect the chip dimension ratios r_h, r_l, and r_w?
2. Based on applying to the hard clay data the same rake-angle effect analysis as done above for the soft clay, does the stiffness of the clay alter the effect of rake angle?
3. Was any difference in resistance (difficulty in turning the hand crank) observed between the two clay stiffnesses? Explain why this observation does or does not make sense.

D.7.3 Data Record

Test #	h (in)	*Clay* (—)	γ_o (deg)	h_c (in)	l_c (in)	w_c (in)
1	⅛	Soft	0			
2	¼	Soft	0			

3	⅛	Hard	0			
4	¼	Hard	0			
5	⅛	Soft	15			
6	¼	Soft	15			
7	⅛	Hard	15			
8	¼	Hard	15			

D.8 Assignment 2 — Orthogonal Cutting

This assignment involves an experiment in which one measures the force required, and shear angle that results, during orthogonal machining. To assess the effects of select process inputs, an independent cut/test will be conducted at each combination of those select process inputs, ranges of which are chosen to span a practically large range of machine settings and tool geometry. The objectives of this assignment are to

- measure machining forces using a force dynamometer,
- measure chip geometry for use in computing shear angle,
- calculate shear yield strength and specific energies, and
- assess shear angle and simple linear specific energy models in terms of how well they capture trends with process inputs.

The report for this assignment should be no more than four (4) pages of text given the report organization and formatting guidelines presented in the Data, Analysis and Reporting section.

D.8.1 The Experiment

D.8.1.1 Apparatus

Cutting tests are conducted on a manual engine lathe that is driven by a DC motor to allow the spindle speed (and therefore surface/cutting speed) to be varied continuously over the lathe's operating range. Orthogonal cutting is achieved by cutting across the entire wall thickness of a tube, at its end, reducing the entire tube cross-section to chips. The feed of the tool parallel to the axis of rotation governs the uncut chip thickness; specifically, given the prescribed orientation of the cutting edge to be noted later, the uncut chip thickness is identical to the distance fed each revolution.

The tubular workpiece has been cut from a long tube stock with a wall thickness of 3.18 mm (0.125 in.). Since the workpiece cross-section is that of a ring, it cannot be supported at the tailstock end, which leaves only the lathe chuck to support one end. This limits the unsupported workpiece length to about five inches to avoid excessive moments, when cutting at the far end, from "bending" the tube out of the chuck. To avoid crushing the tube when tightening the chuck, which would result in insufficient clamping force, a slip-fit plug is inserted into the chuck end of the tube. Upon tightening the chuck, the tube will deform until it contacts the plug, allowing a large clamping force to build with further tightening of the chuck jaws. Besides cutting to length, sample preparation involves cutting a notch along its axis, with a depth of about one-half the wall thickness, and squaring one end relative to its axis. The notch serves as a marker that will remain visible in the cut chips, successive occurrences of which indicate what was originally the circumference of the tube. One end is squared so that when the plug is inserted to meet with the squared end, and subsequently pressed flat against the base of the chuck, the tube axis will be parallel to the axis of rotation.

The cutting tool consists of a flat-faced triangular insert of a plain uncoated tungsten-carbide (WC) grade mounted in a tool holder that orients the cutting edge perpendicular to the axis of rotation. The tool-holder shank is mounted to a force dynamometer via one of a series of adaptor blocks, each offering a different rake angle through the orientation of its square hole into which the tool shank is inserted and locked in place by bolts. The dynamometer is mounted to the lathe carriage via a small tombstone (90° angle-fixture) that allows positioning of the dynamometer in the vertical direction in order to locate the tool edge on center with the workpiece. The radial cross-slide adjustment on the lathe is used to position the cutting edge so that its straight portion spans the tube wall thickness.

The recommended dynamometer is a Kistler piezoelectric, three-component type (model 9257A or model 9265B). The forces measured are in the tangential (cutting) and axial (thrust) directions. The third component is in the radial (lateral) direction; it is recorded, and should be checked to assure that it is small relative to the others, as it should be if orthogonal conditions are achieved as planned. The dynamometer cables carry the electrical charge to the charge amplifier. The voltage signals obtained after charge amplification are passed through a signal conditioner and then to the analog to digital converter of the I/O board in the PC. A virtual instrument designed/written in LabView® is used to record the signal and provide the ability to window-in on a steady-state region of the signal for which an average value is calculated automatically.

D.8.1.2 Tests

The experimental design includes two levels of cutting speed, five levels of uncut chip thickness, and four levels of rake angle. The cutting speed is set as close to the target as possible by adjusting the spindle speed while viewing the surface speed with a hand-held surface-speed tachometer. The uncut chip thickness is identical to the (axial[*]) feed rate setting on the machine, i.e., h [in] = f_r [in/rev] · 1 [rev]. The wall thickness of the tube samples is equivalent to the width of cut. Each team conducts tests at all combinations of cutting speed and uncut chip thickness for their assigned rake angle. The table at the end shows a portion (a test block for a specified rake angle) of the experimental design matrix in standard order. Tests should be conducted in the order specified in the "Order" column.

D.8.1.3 Measurements

The *Data Record* at the end provides spaces for entering data measurements. The measurements include the three force components of the dynamometer, F_x, F_y and F_z, where F_x corresponds to the cutting force, whereas F_z is the thrust force. The average force components are calculated within the data acquisition program from the time series recorded during the cut. Collect a representative chip for each test for measurement of the chip thickness and the chip length (and chip mass as needed). Chips collected for each test should be put into a bag with the test number marked on it and retained for measurement at your leisure after the cutting tests are complete. The width of cut (tube wall thickness) must also be measured for each material

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[*] **Do not engage the radial feed at any time in this testing!**

sample, as there is often variation relative to the specified stock wall thickness. A point micrometer or calipers will suffice for this measurement.

The chip thickness is measured using a point micrometer. Alternatively and preferred, the chip length is measured by wrapping a thread along the chip surface, from notch to notch, and then stretching the thread straight for measurement. If for some reason the notches cannot be seen or the chip is shorter than the notch spacing, the total length can be measured, using a thread as noted above, along with the chip mass as measured with a balance or electronic scale. Material density can be determined by measuring the volume of water displaced by a piece of the work material, of course also knowing its mass. The density can also be identified from a reference book if you have confidence in that reference. When measuring the chip length via the thread, a crude (low resolution) approach is to hold the thread up to an inch or millimeter scale. If using an inch scale, make sure it has resolution down to 1/16 inch or less. A higher resolution approach is to stretch the thread against a piece of cardboard, make marks at each end, then measure with calipers (if possible, precisely cut the cardboard at each mark so the calipers can fit around the cardboard ends).

D.8.2 Data Analysis and Questions

The Test-Set Data worksheet(s) should be similar in form to the Data Record and constructed as follows:

Step 1 Create a data table with the test number, uncut chip thickness (in mm) and cutting speed (in m/min) in the first three columns. There will be twelve rows of data corresponding to all combinations of six uncut chip thickness levels and two cutting speed levels ($6 \cdot 2 = 12$ tests).
Step 2 In columns 4, 5 and 6, enter the cutting and thrust forces (in N).
Step 3 In columns 7, 8 and 9, enter the chip thickness (in mm), length (in mm) and mass (in g).
Step 4 Place column headings in the two rows above each of these nine columns.
Step 5 One cell on the worksheet should contain the width of cut (in mm) for the test set.

D.8.2.1 Size Effect

<u>*Analysis*</u>

To support your answering of the questions below, analyze the repetition-averaged force data <u>for your rake angle level</u> (test block) by creating a scatter plot of each force versus uncut chip thickness, as follows:

Step 1 Create or begin on a new worksheet.
Step 2 In column 1, enter the six uncut chip thicknesses.
Step 3 In columns 2 and 3, enter the respective low-speed and high-speed repetition-averaged cutting force measurements.
Step 4 Create a scatter plot with those three columns, using the values in the first column as the horizontal-axis values.
Step 5 Add two power-law curve-fits, one each to the low- and high-speed cutting force data.
Step 6 Repeat Step 1 through Step 5 to create an identical plot for the thrust force data.

<u>*Questions*</u>

1. Briefly describe the effect of speed, and how it may differ between the cutting and thrust force.

2. The exponent of the uncut chip thickness in the power-law curve-fits, which should lie between zero and one, indicates the strength of the size effect. The strength of the size effect is the degree to which the relation between force and uncut chip thickness departs from a linear relationship. Given that, is the size effect stronger for the cutting force or the thrust force? Briefly explain.
3. Does speed appear to affect the strength of the size effect? Briefly explain.

D.8.2.2 Specific Energy Modeling

Analysis

To support your answering of the questions below, analyze the repetition-averaged data across all rake angles (test blocks) by fitting linear-regression curve-fits, as follows:

Step 1 Create or begin on a new worksheet.
Step 2 In columns 1 and 2, enter the twelve uncut chip thicknesses and cutting speeds.
Step 3 In column 3, enter the low rake angle level for all twelve rows.
Step 4 In column 4, enter the repetition-averaged width of cut for the first data block (lowest rake angle level) in all twelve rows. Using the repetition-averaged width of cut is a short cut (approximation) that is based on the presumption/knowledge that the width of cut is nearly the same across repetitions. If this presumption were not possible, then there would have to be a set of 4 x 12 = 48 rows for each repetition. This short cut is, practically speaking, acceptable given the savings in effort generating the data table.
Step 5 In columns 5 and 6, enter the repetition-averaged cutting and thrust force measurements for the first data block.
Step 6 In columns 7 and 8, compute the specific cutting and thrust energies (in N/mm^2) based on the measured cutting and thrust forces and the (uncut) chip area
Step 7 Copy the twelve rows and create three additional twelve-row blocks for the other three data blocks (rake angles). Then, change the rake angle values in the three new twelve-row blocks to the other three rake angle levels and change the repetition-averaged width of cut and forces to those for the respective data blocks.
Step 8 Apply Excel's LINEST function to each of the specific energies to determine the coefficients of the following linear specific energy model:

$$u_C = b_{0_C} + b_{h_C} h + b_{V_C} V + b_{\gamma_C} \gamma_o \quad \text{and} \quad u_T = b_{0_T} + b_{h_T} h + b_{V_T} V + b_{\gamma_T} \gamma_o \ .$$

Step 9 In columns 9 and 10, compute the natural-log transform the uncut chip thickness and cutting speed.
Step 10 In column 11, compute the natural log of the positive-valued rake-angle function 1 – sinγ_o.
Step 11 In columns 12 and 13, compute the natural-log transform the two specific energies.
Step 12 Again, apply Excel's LINEST function to each of the log-transformed specific energies to determine the coefficients of the following nonlinear (power-law) specific energy model:

$$u_C = b_{0_C} h^{b_{hC}} V^{b_{VC}} (1-\sin\gamma_o)^{b_{\gamma C}} \quad \text{and} \quad u_T = b_{0_T} h^{b_{hT}} V^{b_{VT}} (1-\sin\gamma_o)^{b_{\gamma T}} \ .$$

Questions

1. Which set of models, the linear or power-law, better represents the specific energy behavior with respect to the independent variables? Briefly explain.
2. Explain why the uncut chip thickness exponent of the power-law specific energy models is so different (in sign and magnitude) than the uncut chip thickness exponents for the power-law force curve fits in the previous analysis.

D.8.2.3 Force Model Errors

Analysis

To support your answering of the questions below, analyze the model predictions, as errors relative to the repetition-averaged data across all rake angles, by fitting linear-regression curve-fits, as follows:

Step 1 Use the coefficients that result from the two LINEST model-fits to predict the cutting and thrust force ($F_{\bullet_{Pred}}$) for each of the 48 tests and compute the prediction error ($e_\bullet$) as a percent of the repetition-averaged measurement ($F_\bullet$), i.e.,

$$e_\bullet = \frac{F_\bullet - F_{\bullet_{Pred}}}{F_\bullet} \times 100, \quad \bullet = C, T .$$

Step 2 Apply the LINEST function to create a fit of the errors, for both the cutting and thrust forces, with respect to the three independent variables (h, V, and γ_o). The resulting equations should be

$$e_\bullet = c_{0_\bullet} + c_{h_\bullet} h + c_{V_\bullet} V + c_{\gamma_\bullet} \gamma_o, \quad \bullet = C, T .$$

Step 3 Scale the error-model coefficients (except the intercept $c_{0_\bullet}$) by the average of its respective independent variable to allow comparison of error dependence on each variable via the relative magnitudes of the scaled coefficients. For example,

$$C_{h_\bullet} = c_{h_\bullet} \frac{\sum_{i=1}^{6} h_i}{6}, \quad \bullet = C, T .$$

Step 4 For each error, compute the average, standard deviation, and the product of the standard deviation and the absolute value of the average, which when large despite a small average error, illuminates cases that on average have small error, but have very large variation on each side of zero error, which is not desirable.

Questions

1. Based on the scaled error-model coefficients, comment on how well the models represent the effects of each of the three independent variables.
2. Why is the extra step of parameter scaling for the error models required in order to make any comment in the preceding question?

D.8.2.4 Shear Angle Modeling

Analysis

To support your answering of the questions below, analyze the low-speed shear-angle data (in degrees) by creating a scatter plot, as follows:

Step 1	Create or begin on a new worksheet.
Step 2	In column 1, enter the twelve uncut chip thickness.
Step 3	In column 2, enter the low rake angle level for all twelve rows.
Step 4	In columns 3 and 4, enter the respective repetition-averaged chip thickness (in mm) and chip length (in mm) measurements for the current data block (rake angle).
Step 5	In columns 5 and 6, enter the respective repetition-averaged cutting and thrust force measurements.
Step 6	In columns 7 and 8, compute the chip thickness ratio using the chip thickness and the chip length, respectively.
Step 7	In column 9, compute the friction angle (in degrees), and from it subtract the rake angle.
Step 8	In column 10, compute the orthogonal shear angle (in degrees) based on chip thickness ratio, as calculated using chip thickness or length, whichever seems to be more consistent.
Step 9	Given the expectation that shear angle can be modeled with a form like $$\phi_o = A + B(\beta - \gamma_o),$$ create a scatter plot of the shear angle data versus $\beta - \gamma_o$. Set both axes to range from zero to 45°. Having axis ranges identical on all plots (others to be created next) allows easy visual comparison across all the plots.
Step 10	Next, consider each of the two shear angle models considered in lecture — the Ernst and Merchant model for which the slope is –0.5, and the Lee and Shaffer model for which the slope is –1. The intercept for each of those two models is 45°. Draw each model (45° intercept and respective slope) on the plot using the line tool. These two lines represent where the data would need to lie for the respective model to be valid.
Step 11	Copy the twelve rows and the corresponding plot, and create three additional twelve-row blocks (and respective plots) for the other three data blocks (rake angles). Then, change the rake angle values in the three new twelve-row blocks to the other three rake angle levels and change the repetition-averaged chip thicknesses and lengths, and forces, to those for the respective data blocks.

Questions

1. Based on how well the four rake angle data blocks match one another when plotting the results versus $\beta - \gamma_o$, should the use of $\beta - \gamma_o$ in shear angle models effectively account for the effect of rake angle? Briefly explain.
2. Comment on how well the actual data adheres to the 45° intercept inherent to both shear angle models.
3. Does either shear angle model work well in terms of its slope being a good representation of the data? If so, which one?

D.8.3 Data Record

Test-Set # = _______ ⇒ Rake Angle = ____ (deg)

Date: ________ Names: ________________ WOC: ________ mm

Test Number	**Run Order**	h **(inch)**	V **(ft/min)**	F_x ( )	F_y ( )	F_z ( )	h_c ( )	l_c ( )	m_c ( )
1	5	0.0011	500						
2	1	0.002	500						
3	11	0.0029	500						
4	2	0.0048	500						
5	4	0.0075	500						
6	9	0.0075	500						
7	7	0.0011	800						
8	3	0.002	800						
9	10	0.0029	800						
10	12	0.0048	800						
11	6	0.0075	800						
12	8	0.0075	800						

D.9 Assignment 3 — Corner-Radiused Cutting of Clay

This assignment involves an experiment in which one visually observes the process of corner-radiused cutting followed by measurement of the chips formed. To allow visual observation and physical interaction with the tool and chips both after and during the operation, clay is cut at a magnified scale. The objectives of this assignment are

- to observe the effect of corner radius on chip formation and chip-flow direction,
- to observe the effect of depth of cut on chip formation and chip-flow direction,
- to make basic chip geometry and flow direction measurements, and
- to contrive an analysis approach and write a short report summarizing observations, in particular the effects of corner radius and depth of cut.

The report for this assignment should be no more than two (2) pages of text given the report organization and formatting guidelines presented in the Data, Analysis and Reporting section.

D.9.1 The Experiment

D.9.1.1 Apparatus

The apparatus is identical to that used in Experiment 1. The same cutting tooth is used, but cutting takes place on the radiused ends/corners rather than the straight-edged portion in the middle. The rake angle is maintained at zero and the lead angle, the orientation of the straight-edged portion relative to the horizontal, is zero.

The same plasteline (modeling clay) as used in Experiment 1 is used as the work material; in this experiment, only the softer clay is considered. The same clamping blocks are used, but with an increased height of clay to accommodate the greater vertical immersion required to engage the entire corner radius in the cut. To support the clay under the "depth-direction" loads at the tip of the corner radius, one side of the mold box is retained in the setup. Successive cuts and different feeds are achieved in the same manner that successive cuts and different uncut chip thicknesses were achieved in Experiment 1 — via vertical adjustment of the mill table.

D.9.1.2 Tests

Tests are conducted on a single sample for all combinations of two levels of feed and two levels of depth of cut. The two small-depth cuts should be run first as indicated in the Run Order. These same four tests are then conducted on a second sample using the other corner radius. The different depths of cut are achieved by adjusting the workpiece in the fore-aft direction. At the start of a new block, multiple "entry" passes will be required until the entire corner radius is involved in the cut. These passes also serve as the "clean-up" cut. The first entry pass should remove only a small layer by appropriately positioning the fresh sample in the vertical direction. When changing from a small to a large depth of cut, clean-up cuts will be required starting from the initial point where the initial clean-up cuts commenced.

D.9.1.3 Measurements

The *Data Record* at the end provides spaces for entering data measurements. It is broken into two parts, the first showing the experimental design and space for bulk chip measurements, and the second for localized chip thickness measurements. After each test, measure the direction of chip flow (ρ_c) relative to the perpendicular to the straight-edged portion of the tool, no matter whether the straight-edge portion participated in the cut or not. Chip-flow direction is measured as an angle, being positive when the chip flows away from the corner. It may be easier to make this measurement relative to the straight edge rather than the perpendicular to it, measuring the side that gives an angle less than 90°, then adjust by subtracting from 90°. As a reality check, chip-flow directions should lie between zero and ninety degrees in this experiment. Next, measure the width of the chip using calipers. Finally, using a micrometer, measure the chip thickness at eleven points along its width, being evenly spaced across the chip and two of them corresponding to each end. The location $S_c = 0$ corresponds to the "un-machined" surface; likewise, the measurement at $S_c = 1.0$ should be roughly zero. Measurements should be made on a steady-state chip cross-section. This is achieved by cutting with a sharp knife through the chip (creating the cross-section), perpendicular to the sides of the chip and somewhere in the middle away from the start- and end-of-cut transients (the steady-state region). Note any difficulties encountered in making the chip measurements or performing the cut.

D.9.2 Data Analysis and Questions

The Test-Set Data worksheet (adjusted for the appropriate units) should be similar in form to the Data Record and constructed as follows:

Step 1	Create a data table with the test number, feed (in mm), depth of cut (in mm) and corner radius (in mm) in the first four columns. There will be eight rows of data corresponding to all combinations of two feed levels, two depth of cut levels and two corner radius levels ($2^3 = 8$ tests).
Step 2	In column 5, enter the chip-flow angle (in degrees).
Step 3	In column 6, enter the chip width (in mm).
Step 4	Place column headings in the two rows above each of these six columns.
Step 5	Create a second data table with the test number in the first column.
Step 6	Place a column heading in the two rows above this column.
Step 7	In columns 2-12, enter the local chip thickness (in mm) for each of the evenly-spaced measurements. In the second column-heading row, enter the

normalized chip-width locations, 0.0 through 1.0 with an increment of 0.1 (i.e., 10 evenly spaced measurement increments.

Since there is no repetition of the tests, there is no need for any Test-Block Data worksheets.

D.9.2.1 Corner Radius Effects

Analysis

To support your answering of the questions below, analyze the experiment data, considering here only the small depth-of-cut tests, as follows:

Step 1 Create or begin on a new worksheet.

Step 2 In column 1, enter the feed levels, resulting in two rows.

Step 3 In column 2, enter the respective small-depth–small corner radius chip-flow direction.

Step 4 In column 3, enter the respective small-depth–large corner radius chip-flow direction.

Step 5 In column 4, calculate the change in chip-flow direction as a percent of the chip-flow direction at the small corner radius, i.e.,

$$\Delta\rho_c = \frac{\rho_c\big|_{r_\varepsilon = r_{\varepsilon+}} - \rho_c\big|_{r_\varepsilon = r_{\varepsilon-}}}{\rho_c\big|_{r_\varepsilon = r_{\varepsilon-}}} \times 100 .$$

Step 6 Create a second table by copying the one described above and replacing the chip-flow measurements with the respective width of cut measurements.

Step 7 Create third table of localized chip geometry for the small corner radius, as measured and modeled. In the first column, calculate the normalized chip width locations S_c, noting that $S_c = s_c/w_c$, where s_c is the chip width location and w_c is the chip width. There will be eleven rows corresponding to the eleven columns in the Test-Set Data for Test Number 1.

Step 8 In column 2, enter the localized chip thickness measurements for test 1.

Step 9 In column 3, calculate edge positions s, relative to zero being at the depth-of-cut end, as $s = S_c{\cdot}w$, where w is the straight-edged equivalent width of cut, i.e., the length of cutting edge engaged with the workpiece. Formulate all computations from here forward to be generic with respect to depth of cut (i.e., whether less than or greater than $r_\varepsilon(1 - \sin\psi_r) = r_\varepsilon$, $\psi_r = 0$)!

Step 10 In column 5, compute the local uncut chip thickness for each value of s, noting that it is constant along the lead edge, and a function of approach angle ψ around the corner radius. The equation is

$$h(s) = \begin{cases} f, & s \le d - r_\varepsilon \\ r_\varepsilon + f\cos\psi(s) - \left(r_\varepsilon^{\,2} - f^2\sin^2\psi(s)\right)^{1/2}, & s > d - r_\varepsilon \end{cases},$$

where

$$\psi(s) = \begin{cases} \dfrac{s - (d - r_\varepsilon)}{r_\varepsilon}, & d \ge r_\varepsilon \\ \dfrac{s}{r_\varepsilon} - \sin^{-1}\left(\dfrac{d - r_\varepsilon}{r_\varepsilon}\right), & d < r_\varepsilon \end{cases}, \quad \psi \text{ in radians} .$$

should be calculated in column 4 as an intermediate step. Display $\psi(s)$ in degrees to provide a check (it should range from zero to a little more than 90°, and is only valid when $s > d - r_\varepsilon$. But, be sure to convert $\psi(s)$ back to radians when computing $h(s)$! The relations provided above for $h(s)$ and $\psi(s)$ are simplified for a zero lead angle and by ignoring the free-end condition (for the $h(s)$ equation only) when the depth of cut is less than the corner radius; so, do not use these for non-zero lead angles and small depths of cut outside this exercise.

Step 11 In column 6, calculate the localized chip ratio r_h, i.e., the ratio of cut chip thickness to uncut chip thickness. If the cut chip thickness h_c is zero, set r_h to zero.

Step 12 In row 12 in columns 2, 4 and 6, calculate the average of the above eleven rows in columns 2, 5 and 6, respectively.

Step 13 In row 13 (column 6), calculate the ratio of average cut and uncut chip thicknesses using the values in the twelfth row of columns 2 and 4.

Step 14 Create three more localized chip thickness tables by copying the one described immediately above to compute results for Test Numbers 2, 5 and 6, i.e., all tests at the small depth of cut.

Step 15 Create a scatter plot of localized r_h (i.e., $r_h(s)$) versus $S_c = S$ for each of the four tests.

Questions

1. How, if at all, does the corner radius affect the chip-flow direction and the chip width?
2. Is there much difference in quantifying the average chip thickness ratio as an averaging of the instantaneous ratios as compared to the ratio of the average uncut chip thickness to the average cut chip thickness? Briefly explain why this result does or does not make sense.
3. How, if at all, does the corner radius affect the average cut chip thickness and the ratio of average uncut chip thickness to average cut chip thickness? Does this effect, if it exists, depend substantially on feed?
4. How does the localized chip ratio depend on edge position $S = S_c$?

D.9.2.2 Depth of Cut Effects

Analysis

To support your answering of the questions below, analyze the experiment data by recycling and adjusting the analysis tables from above for analyses here that are identical as indicated, or have the same "form" despite a change in the input variable of interest.

Questions

1. By recycling the (form of the) corner-radius effect analysis done earlier by replacing corner radius with depth of cut and considering only the small corner radius tests, how, if at all, does the depth of cut affect the chip-flow direction?
2. Based on applying to the large-depth data the identical corner-radius effect analysis as done earlier for the small depth of cut, does the depth of cut alter the effect of corner radius on chip-flow direction?
3. By comparing the chip-flow directions for the large-depth–large-corner radius tests to those for the small-depth–small-corner radius tests, comment on how the ratio of depth to corner radius affects chip-flow direction. In other words, since the depth to corner radius ratio is the same in these tests, does that imply the chip-flow direction is virtually the same?

4. Based on applying to the large-depth data the identical corner-radius effect analysis, on localized chip geometry, as done earlier for the small depth of cut, how, if at all, does the depth of cut alter the effect of corner radius on the ratio of average uncut chip thickness to average cut chip thickness?
5. By comparing the ratios of average uncut chip thickness to average cut chip thickness for the large-depth–large-corner radius tests to those for the small-depth–small-corner radius tests, comment on how the ratio of depth to corner radius affects this average chip ratio. In other words, since the depth to corner radius ratio is the same in these tests, does that imply this average chip ratio direction is virtually the same?

D.9.3 Data Record

Inputs and Bulk Measurements

Test Number	Run Order	f (1/8 inch)	d (inch)	$r_{\square}$ (inch)	$^{\circ}{}_{c}$ ( )	w_c ( )
1	1	1	0.75	1		
2	2	2	0.75	1		
3	3	1	1.5	1		
4	4	2	1.5	1		
5	5	1	0.75	2		
6	6	2	0.75	2		
7	7	1	1.5	2		
8	8	2	1.5	2		

Localized Chip Thickness Measurements (□)

Test Number	Normalized Chip-Width Location, S_c (—)										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1											
2											
3											
4											
5											
6											
7											
8											

D.10 Assignment 4 — Corner-Radiused Cutting

This assignment involves an experiment in which one measures the three-dimensional machining force, in terms of its three components of typical interest, when cutting with a corner-radiused tool. The experiment involves three sub-experiments to (1) calibrate the semi-empirical mechanistic force model, and (2) validate the model across the calibration envelope. The objectives of this assignment are to

- measure the cutting, feed and depth components of the machining force present while cutting with a corner-radiused tool,
- study force component trends with respect to process inputs, in particular those specific to corner-radiused tools (corner radius and lead angle),
- calculate and empirically model nonlinear specific energies, and
- assess the capability of the force model to predict specific energy, straight-edged equivalent cutting and thrust force components, and ultimately each of the three force components originally measured.

The report for this assignment should be no more than four (4) pages of text given the report organization and formatting guidelines presented in the Data, Analysis and Reporting section.

D.10.1 The Experiment

D.10.1.1 Apparatus

The apparatus is virtually identical to that used in Experiment 2 with the primary difference being the workpiece. The manual engine lathe used in a standard OD bar-turning arrangement. The workpiece is a solid bar of the same material as used in Experiment 2. It is fixtured by clamping it in the lathe chuck and axially pinching it with a live center to support it at the tailstock end.

Like in Experiment 2, flat-faced triangular inserts of the same plain uncoated tungsten-carbide (WC) grade are mounted in a tool holder. Different inserts are used to provide the different levels of corner radius as specified in the experimental design. Different tool holders are used to orient the cutting edge at the different lead angle levels as specified in the experimental design. Each tool holder has been modified to provide fully neutral rake geometry — zero back rake angle and zero side rake angle.

Mounting of the tool holder to the dynamometer and the dynamometer to the machine via a tombstone is identical to the Experiment-2 setup. The forces measured are in the tangential (cutting), axial (feed) and radial (depth) directions. The connection to the PC-based data acquisition system and the LabView® virtual instrument are also identical to those in Experiment 2.

D.10.1.2 Tests

There are three two-level full-factorial experimental designs for this experiment — one for model calibration, a second for speed-and-feed validation, and a third for depth-of-cut validation. As in Experiment 2, the cutting speed is set as close to the target as possible by adjusting the spindle speed while viewing the surface speed with a hand-held surface-speed tachometer. The feed is identical to the (axial[*]) feed rate setting on the machine, i.e., $f\,[\text{in}] = f_r\,[\text{in/rev}] \cdot 1\,[\text{rev}]$. The depth of cut is set using the radial cross-slide; remember that manual lathes usually indicate the change in workpiece diameter on the radial cross-slide adjustment scale, meaning that the scale corresponds to twice the depth of cut.

Each team conducts a subset of each of the following experimental designs — that is, all combinations of all variables except corner radius and lead angle, which are held constant (blocked) at the team's assigned combination of corner radius and lead angle.

1. The model calibration sub-experiment includes cutting speed, feed, corner radius and lead angle as the independent variables. For these tests, the depth of cut is held constant at the value specified in the experimental design.

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[*] **Do not engage the radial feed at any time in this testing!**

2. The speed-and-feed validation sub-experiment is identical to the model calibration design in structure and depth of cut used. The levels of cutting speed and feed are set within their respective ranges used in the calibration experiment.
3. The depth-of-cut validation sub-experiment considers the same variables (cutting speed, feed, corner radius and lead angle) and levels of those variables as the calibration design. In addition, depth of cut is introduced as a fifth independent variable taking on low and high levels below and above, respectively, the depth of cut used in the other designs.

Tables at the end show in standard order a team's portion (i.e., for their test block, or corner-radius – lead-angle combination) of each experimental design matrix.

Although it is typically important to randomize the test order, the small size of the first two sub-designs ($2^2 = 4$ tests) makes randomization ineffective. The depth-of-cut validation sub-design is larger ($2^3 = 8$ tests), but, for convenience, randomization is not employed and the tests are blocked on depth of cut in addition to blocking on corner radius and lead angle.

D.10.1.3 Measurements

The *Data Record* at the end provides spaces for entering data measurements. It is broken into three parts, one for each of the sub-experiments.

The measurements for each sub-experiment include the three force components of the dynamometer, F_x, F_y and F_z, where F_x and F_y roughly (in some cases exactly) correspond to the cutting and depth forces, respectively, whereas F_z is the feed force. The average force components are calculated within the data acquisition program from the time series recorded during the cut.

D.10.2 Data Analysis and Questions

The Test-Set Data worksheet(s) should be similar in form to the Data Record and constructed as follows:

Step 1 Create a data table for the model-calibration sub-experiment with the test number, feed (in mm), cutting speed (in m/min) and depth of cut (in mm) in the first four columns. There will be four rows of data corresponding to all combinations of two feed levels and two cutting speed levels ($2 \cdot 2 = 4$ tests).

Step 2 In columns 5, 6 and 7, enter the cutting, feed and depth forces (in N).

Step 3 Place column headings in the two rows above each of these seven columns.

Step 4 Merge the row of cells above the column headings and enter a table heading, such as "Model Calibration Sub-Experiment".

Step 5 Repeat Step 1 through Step 4 for the speed-and-feed validation sub-experiment. Place the data table in the same seven columns in blocks of rows below the model-calibration sub-experiment. The column headings are the same. The table heading might be "Speed-and-Feed Validation Sub-experiment".

Step 6 Repeat Step 1 through Step 4 for the depth-of-cut validation sub-experiment. Place the data table in the same seven columns in blocks of rows below the speed-and-feed validation sub-experiment. The column headings are the same. The table heading might be "Depth-of-Cut Validation Sub-experiment".

D.10.2.1 Model Calibration — Zero Corner Radius Approximation

Analysis

To support your answering of the questions below, analyze the repetition-averaged data of the model-calibration sub-experiment, for your corner-radius–lead-angle combination (test block) by fitting the nonlinear specific energy models

$$u_C = b_{0_C} h^{b_{h_C}} V^{b_{V_C}} \qquad \text{and} \qquad u_T = b_{0_C} h^{b_{h_T}} V^{b_{V_T}}$$

to the data, as follows:

Step 1 Create or begin on a new worksheet.

Step 2 In columns 1-3 enter the feed, cutting speed and depth of cut for the four model-calibration test.

Step 3 In columns 4-6, enter the respective repetition-averaged cutting, feed and depth forces.

Step 4 In column 7, compute the uncut chip thickness (in mm) based on a zero corner radius approximation, i.e., $h = f\cos\psi_r$, ψ_r being the lead angle.

Step 5 In column 8, enter the cutting speed.

Step 6 In column 9, compute the straight-edged equivalent cutting force (in N) based on the repetition-averaged cutting force.

Step 7 In column 10, compute the straight-edged equivalent thrust force (in N) based on the repetition-averaged feed and depth forces.

Step 8 In columns 11 and 12, compute the specific cutting and thrust energies u_C and u_T (in N/mm^2) based on the respective measured force components and the known chip area $a = f{\cdot}d$.

Step 9 In columns 13-16, so that linear regression modeling can be used, natural-log transform the uncut chip thickness, cutting speed, and two specific energies to obtain independent variables $X_1 = \ln h$ and $X_2 = \ln V$ and responses $y_1 = \ln u_C$ and $y_2 = \ln u_T$.

Step 10 In columns 17 and 18, code the independent variables X_1 and X_2 into x_1 and x_2, respectively. This can be done by inspection, but it may be a good exercise to implement it via the coding transformation.

Step 11 Determine the coefficients of the two models relating the transformed responses (y_1 and y_2) to the coded–transformed independent variables x_1 and x_2. This may be done using either the Excel LINEST function or the DOE modeling technique based on mean response and main effects of the two-level factorial design.

Step 12 For more convenient use the models should be de-coded to obtain estimation models of y_1 ($\ln u_{u_C}$) and y_2 ($\ln u_T$) as functions of $X_1 = \ln h$ and $X_2 = \ln V$, specifically

$$\hat{y}_2 = \ln \hat{u}_C = b_{0_C} + b_{h_C} \ln h + b_{V_C} \ln V = B_{0_C} + B_{1_C} X_1 + B_{2_C} X_2$$

and

$$\hat{y}_2 = \ln \hat{u}_T = b_{0_T} + b_{h_T} \ln h + b_{V_T} \ln V = B_{0_T} + B_{1_T} X_1 + B_{2_T} X_2 \,,$$

or, in power-law form as

$$\hat{u}_C = \mathrm{e}^{b_{0C}} h^{b_{hC}} V^{b_{VC}} \qquad \text{and} \qquad \hat{u}_T = \mathrm{e}^{b_{0T}} h^{b_{hT}} V^{b_{VT}}$$

Questions

1. If the strength of the size effect is quantified by how negative the uncut chip thickness exponent is, with more negative being a stronger size effect, is the size effect stronger for the cutting or thrust direction? Is this expected?
2. Are the model coefficients different or the same (round-off errors aside) for the coded and decoded models? Briefly explain why this is the case.
3. If the coefficients of the coded and decoded models are different, are the relative strengths of the effects in the cutting direction as compared to the thrust direction different in the two models? In other words, what happens to the ratio of each coefficient in the cutting direction to the respective coefficient in the thrust direction (e.g., b_{h_C}/b_{h_T}) when going from the coded to decoded space?

D.10.2.2 Model Calibration — Nonzero Corner Radius

Analysis

To support your answering of the questions below, analyze the model-calibration sub-experiment exactly the same as in the above analysis (a good way is to make a copy of that worksheet as a start), with the exception of calculating uncut chip thickness as an average, as influenced by not only the lead angle but also the corner radius, i.e., replace $h = f\cos\psi_r$ with $\bar{h} = a/w = fd/w$.

Questions

1. In comparison to the coded model achieved under the zero corner radius approximation, which coded model parameters, if any, have changed under the nonzero corner radius approach? Briefly explain why this makes sense or not.
2. In comparison to the decoded model achieved under the zero corner radius approximation, which decoded model parameters, if any, have changed under the nonzero corner radius approach? Briefly explain why this makes sense or not.

D.10.2.3 Effects of Speed, Feed and Depth of Cut on Edge-Local Forces

Analysis

To support your answering of the questions below, analyze repetition-averaged data of both validation sub-experiments, for your corner-radius–lead-angle combination, to compare measured edge-local (cutting and thrust) forces to model predictions using both the zero- and nonzero corner radius models developed above, as follows:

Step 1 Create or begin on a new worksheet.
Step 2 Create a data table for the for the speed-and-feed validation sub-experiment using the zero corner radius approximation model.
Step 3 In columns 1-3, enter the feed, cutting speed and depth of cut
Step 4 In columns 4-6, enter the respective repetition-averaged cutting, feed and depth forces.
Step 5 In column 7, compute the straight-edged equivalent cutting force (in N) based on the repetition-averaged cutting force.
Step 6 In column 8, compute the straight-edged equivalent thrust force (in N) based on the repetition-averaged feed and depth forces.
Step 7 In columns 9 and 10, using the zero corner radius approximation model, compute the cutting and thrust forces (in N) based on the model predicted specific energies.

Step 8 In columns 11 and 12, compute the prediction errors ($e_\bullet$) as a percent of the repetition-average force measurement ($F_\bullet$), i.e.,

$$e_\bullet = \frac{F_\bullet - F_{\bullet_{Pred}}}{F_\bullet} \times 100, \quad \bullet = C, T\,.$$

Step 9 In the first three rows below their respective columns, compute for the two errors the average, the standard deviation, and the product of the standard deviation and the absolute value of the average error. The third quantity amplifies small average errors in cases where the error fairly evenly spans zero percent, but does so across a large range (high standard deviation) which is another mode of model inaccuracy as opposed to large average error alone.

Step 10 In a block of rows below the block created above, repeat Step 2 through Step 9 using the nonzero corner radius model.

Step 11 In two blocks of rows below the two created above, repeat Step 2 through Step 10 for the depth-of-cut validation sub-experiment.

Questions

1. For the <u>speed-and-feed</u> validation sub-experiment, and considering the cutting and thrust directions separately, which model (zero or nonzero corner radius) if either provides better predictive capability? Briefly explain why this does or does not make sense.
2. Answer the above question for the <u>depth-of-cut</u> validation sub-experiment. Again, briefly explain why this does or does not make sense.

D.10.2.4 Effects of Speed and Feed on Tooth-Local Forces

Analysis

To support your answering of the questions below, analyze <u>all</u> Speed-and-Feed Validation data, meaning <u>all corner-radius–lead-angle combinations</u>, to assess the predictive capabilities of <u>only</u> the nonzero corner radius model in terms of the tooth-local (cutting, feed and depth) forces, as follows:

Step 1 Create or begin on a new worksheet.

Step 2 Create a data table for the speed-and-feed validation sub-experiment.

Step 3 In columns 1-3, enter the feed, cutting speed and depth of cut for the four speed-and-feed validation test conditions.

Step 4 In columns 4-6, enter the respective repetition-averaged cutting, feed and depth forces.

Step 5 In columns 7 and 8, enter the respective lead angle and corner radius.

Step 6 In columns 9 and 10, compute the specific cutting and thrust energies (in N/mm^2).

Step 7 In column 11, compute the equivalent lead angle (in degrees) using Fu's method.

Step 8 In columns 12-14, compute the cutting, feed and depth forces (in N) using the specific energies, the chip area and equivalent lead angle.

Step 9 In columns 15-17, compute the prediction error (%) in the same manner as in the previous analysis.

Step 10 As in the previous analysis, calculate the average, standard deviation, etc. for the errors in the three force components.

Step 11 Copy the four rows and create three additional four-row blocks for the other three data blocks (corner-radius–lead-angle combinations). Then, change the lead angle and corner radius values in the three new four-row blocks to their appropriate levels and change the repetition-averaged force references in the error computations to those of the respective data blocks.

Questions

1. Comment on the ability of the model to predict these three tooth-local force components, compared to how well the same model predicts the edge-local (cutting and thrust) force components for a single corner radius and lead angle as seen in the previous analysis.

D.10.2.5 Effects of Depth of Cut on Tooth-Local Forces

Analysis

To support your answering of the question below, analyze all Depth-of-Cut validation data, meaning all corner-radius–lead-angle combinations, exactly the same as in the above analysis where in this case there will be four eight-row blocks instead of four four-row blocks.

Questions

1. Comment on the ability of the model to predict these three tooth-local force components, compared to how well the same model predicts the edge-local (cutting and thrust) force components for a single corner radius, lead angle and depth of cut as seen in the previous two analyses.

D.10.3 Data Record

Test-Set # = _______ ⇒ Corner Radius = _______ (   ), Lead Angle = ______ (degrees)

Date: ____________ Names: ____________

Model Calibration Sub-experiment

Test Number	Run Order	f (inch)	V (ft/min)	d (inch)	F_x ( )	F_y ( )	F_z ( )
MC1	1	0.002	500	0.08			
MC2	2	0.012	500	0.08			
MC3	3	0.002	800	0.08			
MC4	4	0.012	800	0.08			

Speed-and-Feed Validation Sub-experiment

Test Number	Run Order	f (inch)	V (ft/min)	d (inch)	F_x ( )	F_y ( )	F_z ( )
SFV1	1	0.005	600	0.08			
SFV2	2	0.009	600	0.08			
SFV3	3	0.005	700	0.08			
SFV4	4	0.009	700	0.08			

Depth-of-Cut Validation Sub-experiment

Test Number	Run Order	f (inch)	V (ft/min)	d (inch)	F_x ( )	F_y ( )	F_z ( )
DV1	1	0.002	500	0.02			
DV2	2	0.012	500	0.02			
DV3	3	0.002	800	0.02			
DV4	4	0.012	800	0.02			
DV5	5	0.002	500	0.1			
DV6	6	0.012	500	0.1			
DV7	7	0.002	800	0.1			
DV8	8	0.012	800	0.1			

D.11 Assignment 5 — Milling Force Prediction

This assignment involves an experiment in which one measures the three global force components during face milling. The objectives of this assignment are to

- measure the three global force components in a milling operation,

- estimate and assess the effects of runout via matching of the model predicted force signature shape to the measured force signature shape,
- observe the effects of D_t/W_w (tool-diameter to work-width ratio), and
- assess the capability of a force model coefficient obtained in a separate experiment to predict forces under substantially different kinematics.

The report for this assignment should be no more than two (2) pages of text given the report organization and formatting guidelines presented in the Data, Analysis and Reporting section.

D.11.1 The Experiment

D.11.1.1 Apparatus

Cutting tests are conducted on a CNC machining center or milling machine. The workpiece is a solid block of the same material as used in Experiments 2 and 4. It is fixtured by clamping it in a vice attached to a three-component piezoelectric dynamometer. The cutting inserts are flat-faced and of the same un-coated tungsten-carbide grade as used in previous metal-cutting experiments, and expected to have the same edge (bluntness) condition. A zero corner radius is achieved by grinding off the corner on available standard tooling; this allows the focus here to lie on the effects of, milling kinematics and D_t/W_w ratio, and the ability to predict those effects, rather than focusing on the corner radius effects already studied in Experiment 4. The face-milling cutter has four or six evenly spaced teeth with rake geometry falling in the range of rake angle considered in Experiment 2. The specific values of rake angles, lead angle and cutter diameter are provided at testing time. The dynamometer signals are recorded using the same PC-based data acquisition system and the LabView® virtual instrument as used in previous experiments.

D.11.1.2 Tests

The experimental design is a simple two-variable, two-level (2^2) full factorial design. The tool geometry and spindle/cutting speed are held constant while only feed rate and workpiece width are varied. The workpiece width levels include one greater than the tool diameter ($D_t/W_w < 1$), and one less than or equal to the tool diameter ($D_t/W_w = 1$, effectively).

Although it is typically important to randomize the test order, the small size of the experimental design ($2^2 = 4$ tests) makes randomization ineffective.

D.11.1.3 Measurements

The dynamometer signals for F_x, F_y, and F_z are recorded and stored as a time series rather than a simple average value as in the previous metal-cutting experiments. Since there will be hundreds of values (time steps) for each force recorded for each test, it is impractical for the *Data Record* below to provide space for data entry. Data will be entered into the analyses by cutting and pasting from the tab-delimited columnar files stored to disk from the data acquisition system.

The measurements for each sub-experiment include the three force components of the dynamometer, F_x, F_y and F_z, which will be referred to as F_{x_d}, F_{y_d} and F_{z_d} where the sub-subscript 'd' indicates these are in the dynamometer coordinates. Note that the dynamometer coordinate system (axes) may not match those of the process as modeled, hence the differentiation by adding the 'd' sub-subscript. Furthermore, the forces measured are those acting on the workpiece will be equal and opposite those acting on the tool — the forces considered in all models presented. Therefore, when processing the data prior to analysis, adjustments to the data are made by flipping signs and assigned direction to account for these differences. For example, these adjustments could be of the form $F_x = F_{y_d}$, $F_y = -F_{x_d}$ and $F_z = -F_{z_d}$, where F_x, F_y and F_z are the forces acting on the tool in the model coordinate frame.

D.11.2 Data Analysis and Questions

Since it is not practical to consider repetition of tests when observing a time series of force measurements, each set of tests is considered as a test-set of its own. Furthermore, since the quantity of data is quite large, and hence it is not efficient to re-summarize the data in its own worksheet, selection of the test-set number introduces the correct data directly into the analysis.

D.11.2.1 Model Prediction Assessment

Analysis

To support your answering of the questions below, analyze the measured force data series, from each test, by comparing them to model predictions. Use the spreadsheet implementation of the milling force prediction model to estimate tooth throw and axis offset en route to assign the predictive capability of the force model calibration determined in Experiment 2. Complete the spreadsheet as follows:

Step 1 Enter the equation for the tangential force acting on each tooth as a function of the cutting and thrust force components acting on the respective tooth.

Step 2 Enter the equation for the longitudinal and radial forces acting on each tooth as a function of the cutting and thrust force components acting on the respective tooth.

Step 3 Enter the equation for the x-direction force acting on each tooth as a function of the tangential, longitudinal and radial force components acting on the respective tooth.

Questions

1. By ‘playing’ with the runout parameters to match the measured force signal (if needed), **briefly** discuss the runout that may or may not be present in the experimental setup.
2. Comment on the accuracy of the model predictions and what may be the cause of any errors.

D.11.3 Data Record

Date:

Names:

Experiemental Design

Test Number	Run Order	f_t (inch/t)	f_r (inch/rev)	n_s (rpm)	d (inch)	W_w ( )
1	1	0.002	0.008	764	0.1	
2	2	0.004	0.016	764	0.1	
3	3	0.002	0.008	764	0.1	
4	4	0.004	0.016	764	0.1	

Enter sampling frequency here, or enter a series of time points in each time column. ↓ ↓

Force Series ( )

Sampling Freq: **Hz**

Test 1				Test 2				Test 3				Test 4			
Time	F_x	F_y	F_z	Time	F_x	F_y	F_z	Time	F_x	F_y	F_z	Time	F_x	F_y	F_z
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓

D.12 Assignment 6 — Form Error and Finish in Turning

This assignment involves an experiment in which one measures the variation in machined diameter and surface finish with axial position and how each is affected by changes in corner-radiused tooth geometry and feed rate. The objectives of this assignment are to

- measure the diameter variation as a function of axial position,
- measure the surface finish variation as a function of axial position,
- assess the dependence of form error and surface finish on tooth geometry and feed rate,
- assess the accuracy of a beam-based model of workpiece stiffness, and
- asses the accuracy of surface finish models.

The report for this assignment should be no more than two (2) pages of text given the report organization and formatting guidelines presented in the Data, Analysis and Reporting section.

D.12.1 The Experiment

D.12.1.1 Apparatus

The apparatus is virtually identical to that used in Experiments 2 and 4 with the primary difference being the workpiece. The manual engine lathe used in a standard OD bar-turning arrangement like in Experiment 4. While the workpiece is a solid bar of the same material as used in Experiments 2 and 4, it is noticeably slender, i.e., having a large length-to-diameter ratio, L_w/D_w. It is fixtured by clamping it in the lathe chuck and, if $L_w/D_w > 6$,by axially pinching it with a live center to support it at the tailstock end.

Like in Experiment 4, flat-faced triangular inserts of the same plain uncoated tungsten-carbide (WC) grade are mounted in a tool holder. Different inserts are used to provide the different levels of corner radius as specified in the experiment design. Different tool holders are used to orient the cutting edge at the different lead angle levels as specified in the experiment design. Each tool holder has been modified to provide fully neutral rake geometry — zero back rake angle and zero side rake angle.

Mounting of the tool holder to the dynamometer and the dynamometer to the machine via a tombstone is identical to the Experiment-4 setup. The same forces — tangential (cutting), axial (feed) and radial (depth) — are measured. The connection to the PC-based data acquisition system and the LabView® virtual instrument are also identical to those of Experiments 2 and 4.

D.12.1.2 Tests

The design for this experiment is a three-variable full-factorial design with two levels of two variables (corner radius and lead angle) and ten levels of the third (axial position). A fourth variable, feed rate, is introduced in an ad-hoc though educated manner. Other parameters to be held constant include spindle speed, depth of cut, and workpiece length and diameter. As in Experiment 2, the spindle speed is set as close to the target as possible by adjusting the spindle speed while viewing the surface speed with a hand-held tachometer. In setting the depth of cut, remember that manual lathes usually indicate the change in workpiece diameter on the radial cross-slide adjustment scale, meaning that the scale corresponds to twice the depth of cut.

Each team conducts a subset of the experiment design — that is, all axial positions and related feed rates while holding corner radius and lead angle constant at the team's assigned combination of corner radius and lead angle. A table at the end shows a team's portion of the experiment design matrix.

Although it is typically important to randomize the test order, it does not make sense (for axial position) since it is natural for the cut to go continuously from one end to the other. Regarding the corner radius and lead angle, by nature of each cut going from one end to the other without interruption and having only two levels of each, their randomization is not practical.

D.12.1.3 Measurements

The *Data Record* at the end provides spaces for entering data measurements. The measurements for each corner-radius – lead-angle combination include for each axial position the machined diameter, surface finish (as roughness average) and the three force components of the dynamometer, F_x, F_y and F_z, where F_x and $-F_y$ correspond to the cutting and depth forces, respectively, and F_z is the feed force. The average force components are determined within the data acquisition program from the time series recorded during the cut.

To facilitate locating the measurement points on the workpiece and in the recorded, it is desirable to leave identifying marks at the machined workpiece and in the recorded force signal, marks that also serve to synchronize the two. This is accomplished by stopping the feed for a few seconds, then re-engaging the feed, as the start/end of each measurement element that spans each axial position of interest. Stopping the feed will leave a dwell mark on the part and a visible drop in the force signal. Measurements should be made at the midpoint between the dwells. To facilitate stopping the feed at the right axial positions, marks are made on the workpiece at the start/end of each axial element. Marks made around the circumference with a black felt-tip marker will be visible while cutting.

D.12.2 Data Analysis and Questions

The Test-Set Data worksheet(s) should be similar in form to the Data Record and constructed as follows:

Step 1 Create a data table with the axial position from tailstock (in mm) in the first column. There will be ten rows of data corresponding to the ten axial measurement locations. The axial position is the average of its start and end points in the Data Record.
Step 2 In column 2, enter the feed (in mm), which is equivalent to the feed per revolution (multiplied by one revolution).
Step 3 In columns 3, 4, 5, 6 and 7, enter the final workpiece diameter (in mm), roughness average (in µm), and the cutting, feed and depth forces (in N).
Step 4 Place column headings in the two rows above each of these seven columns.
Step 5 Merge the row of cells above the column headings and enter a table heading, such as "Measurements".

D.12.2.1 Effects of Tooth Geometry on Form Error and Finish

Analysis

To support your answering of the questions below, analyze all the repetition-averaged data by plotting diameter deviation from the target and surface finish against axial position. Make one plot showing two graphs, one for each lead angle, holding corner radius constant. Make a second plot showing two graphs, on for each corner radius, holding lead angel at its high level. Do so as follows:

Step 1 Create or begin on a new worksheet.
Step 2 In columns 1 and 2 enter the axial position (from the chuck) and feed rate. There will be ten rows of data corresponding to the ten axial measurement locations.
Step 3 In columns 3-6, compute the diameter deviations as the measured repetition-averaged diameter less the target diameter.
Step 4 In columns 7-10, enter the repetition-averaged roughness averages.
Step 5 Create one plot for the diameter deviation data.
Step 6 Create one plot for the surface roughness data.

Questions

1. How does diameter deviation change with axial position? Describe why this makes sense or not.
2. How does diameter deviation change with lead angle? Describe why this makes sense or not.
3. How does diameter deviation change with corner radius? Describe why this makes sense or not.
4. How does roughness average change with axial position? Describe why this makes sense or not.
5. How does roughness average change with lead angle? Describe why this makes sense or not.
6. How does roughness average change with corner radius? Describe why this makes sense or not.

D.12.2.2 Form-Error Modeling

Analysis

To support your answering of the questions below, analyze repetition-averaged data of both validation sub-experiments, for your corner-radius–lead-angle combination, to compare measured diameter deviations with those predicted by applying measured forces to s simple beam model. Assume the workpiece cross-section does not change as it is cut, meaning that its diameter at all times is assumed to be the initial diameter. Do so as follows:

Step 1 Create or begin on a new worksheet.
Step 2 Create a data table made up of ten columns as described below.
Step 3 In columns 1 and 2 enter the axial position (from the chuck) and feed rate. There will be ten rows of data corresponding to the ten axial measurement locations.
Step 4 In column 3, compute the stiffness of the workpiece. If there is a tailstock, consider it as a fixed-pinned (chuck-tailstock) beam, otherwise a cantilevered (at chuck) beam.
Step 5 In columns 4 and 5, enter the repetition-averaged tangential and radial force measurements.
Step 6 In columns 6 and 7, compute the tangential and radial workpiece deflections predicted based on the measured force components and predicted stiffness. Divide each by the feed to account for the changes in feed, which makes it easier to assess effects of axial position via stiffness.
Step 7 In column 8, compute the repetition-averaged diameter deviation as the measured diameter less the target diameter. Again, divide each by the feed.
Step 8 In column 9, compute the predicted diameter deviation as the radial distance from the tip of the (rigid) tool to the displaced axis of the workpiece.
Step 9 In column 10 compute the error in the diameter deviation prediction, as a percent of the measured value, such that an under-prediction gives a negative error.
Step 10 Create one plot showing the measured and predicted diameter deviations, as a function of axial position.
Step 11 Create a second plot showing the percent error in the predicted diameter deviation, as a function of axial position.
Step 12 Below the above table and plots, create a copy of the table and plots.
Step 13 Change the forces to be those predicted using the force model coefficients determined in Experiment 4 by computing average uncut chip thickness (in mm), cutting speed (in m/min), and a rake angle of zero. Use Fu's method for computing equivalent lead angle.

Questions

1. Is the workpiece well represented as a beam with the boundary conditions noted (fixed-pinned or cantilevered)? Explain why or why not, and if not, what might be the cause of the discrepancies?
2. Does the force model, irrespective of the "goodness" of the beam model, work well in predicting the diameter deviation? Explain why or why not, and if not, what aspect of the force model might be the cause.

D.12.2.3 Surface-Finish Modeling

Analysis

To support your answering of the questions below, analyze all the repetition-averaged data to compare measured surface finish to that predicted using Boothroyd's equation and an analytically derived result that comes from integrating equations for $|r(z) - r_{cl}|$, as follows:

Step 1 Create or begin on a new worksheet.
Step 2 Create a data table made up of fourteen columns as described below.
Step 3 In columns 1 and 2 enter the axial position (from the chuck) and feed rate. There will be ten rows of data corresponding to the ten axial measurement locations.

Step 4 In columns 3-6, enter the repetition-averaged roughness average value for the four corner-radius – lead-angle combinations.

Step 5 In columns 7-10, use Boothroyd's equation to compute the roughness average for the four corner-radius – lead-angle combinations.

Step 6 In columns 11-14 compute the errors in the prediction, as a percent of the measured value, such that an under-prediction gives a negative error.

Step 7 In a block of rows below the block created above, repeat Step 3 through Step 6.

Step 8 In the columns of roughness average measurements (columns 3-6), replace those values by computing the centerline value using the analytically derived equation

$$r_{cl} = r_\varepsilon - \frac{f}{4}\left[4\left(\frac{r_\varepsilon}{f}\right)^2 - 1\right]^{1/2} - \frac{r_\varepsilon^{\,2}}{f}\sin^{-1}\left(\frac{f}{2r_\varepsilon}\right),$$

or in non-dimensional form,

$$R_{cl} = 1 - \frac{F}{4}\left[4F^{-2} - 1\right]^{1/2} - \frac{1}{F}\sin^{-1}\left(0.5F\right),$$

where R_{cl}, R_a and F are their respective lower case variables divided by r_ε.

Step 9 In the columns of roughness average prediction (columns 7-10), replace those values by computing the roughness average value using the analytically derived equation

$$r_a = \frac{2}{f}\left(r_{cl} - r_\varepsilon\right)\left(2r_\varepsilon r_{cl} - r_{cl}^{\,2}\right)^{1/2} + \frac{2r_\varepsilon^{\,2}}{f}\sin^{-1}\left(\frac{\left(2r_\varepsilon r_{cl} - r_{cl}^{\,2}\right)^{1/2}}{r_\varepsilon}\right),$$

or in non-dimensional form,

$$R_a = \frac{2}{F}\left\{\left(R_{cl} - 1\right)\left(2R_{cl} - R_{cl}^{\,2}\right)^{1/2} + \sin^{-1}\left(\left(2R_{cl} - R_{cl}^{\,2}\right)^{1/2}\right)\right\}.$$

Step 10 Make sure the error columns (11-14) are referencing the measured values to compute the percent errors in rough ess average value.

<u>Questions</u>

1. Based on the first section of the analysis (Sec. D.12.2.1), the dependence of surface finish on axial position was assessed. Do one or both models agree with that finding?
2. Assess the accuracy of the two models relative to one another in terms of how well they capture the effect of corner radius and lead angle.

D.12.3 Data Record

Date:

Contact:

Test-Set:

Lead Angle: degrees

Corner Radius: 1/64 inch

Measurements

Axial Elements (inch, Tailstock)	Feed Rate (inch/rev)	D_{wf} ( )	r_a ( )	F_x ( )	F_y ( )	F_z ( )
0 to 0.9	0.008					
0.9 to 1.8	0.008					
1.8 to 2.7	0.004					
2.7 to 3.6	0.004					
3.6 to 4.5	0.004					
4.5 to 5.4	0.004					
5.4 to 6.3	0.004					
6.3 to 7.2	0.004					
7.2 to 8.1	0.0058					
8.1 to 9	0.0058					

Comments / Notes / Other Observations

Axial Elements (inch, Tailstock)	
0 to 0.9	
0.9 to 1.8	
1.8 to 2.7	
2.7 to 3.6	
3.6 to 4.5	
4.5 to 5.4	
5.4 to 6.3	
6.3 to 7.2	
7.2 to 8.1	
8.1 to 9	