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The advancement of the lathe and subsequent modern technologies was made possible through research leading to the development of optimization tables that list specific feed rates, spindle speeds, and depths of cut for different materials. These tables are the standard used in industry as a source of reference, when making a change from one job to another where the machining parameters of each may be quite different. The time, material, and tooling costs associated with the experimental steps needed to find the appropriate machining parameters for each new job are eliminated, giving the company the advantage of a reduction in setup costs and improved product quality.

While there are many machining optimization parameters that have been developed and put into tables, an area that has been overlooked is that of correlation between the unsupported workpiece extension length and the resultant surface roughness. The premise of this research is that the use of a tailstock in lathe work for workpiece support may sometimes be unnecessary. This idea is investigated to find out if there are instances where an unsupported workpiece can be machined with equivalent results to a supported workpiece in terms of surface roughness; so the time, labor, and materials used to center drill the workpiece and setup the tailstock are not used needlessly. Therefore, the focus of this study is to extend previously established research on effects of workpiece elastic deformations (Benardos, Mosialos and Vosniakos, 2006) and examine the relationship that exists between the length, at a specific diam-

eter, and surface roughness of bar stock in both supported and unsupported turning operations in an attempt to reduce setup waste in turning operations.

Literature Review

Since the invention of the modern engine lathe, researchers have been contributing to the body of knowledge that will optimize the lathe's productivity and quality (i.e. surface roughness). Surface roughness plays an important role in product quality and is an especially important design characteristic in many products that are subject to precision fits, fastener holes, fatigue loads and aesthetic requirements (Wang, 2001, Feng & Wang, 2002, and Kalpakjian et al. 2006). Dimensional accuracy also, together surface roughness greatly affect useful part life, especially in cases in which the components will be in moving contact with other elements or materials.

Recent research that has identified the relationship between surface roughness and lesser understood turning parameters include; surface roughness versus lubrication and bed material (Bruni, Forcellese, Gabrielli & Simoncini, 2006), surface roughness versus tool wear (Pavel, Marinescu, Deis & Pillar, 2005), surface roughness versus burnishing feed rate, force, and speed (El-Axir & Ibrahim, 2005), and surface roughness versus dry turning (Thomas & Beauchamp, 2003). Kalpakjian et al. (2006) illustrates a regressing relationship between dimensional tolerance and workpiece length, but does not adequately differentiate the surface roughness correlation between a supported

and unsupported workpiece in relation to its length.

The practice of choosing appropriate process parameters can be quite difficult. To make this determination currently requires time consuming trial and error experimentation which is costly in time and material resources. The solution to this dilemma, according to Wang (2001), is to develop a chart to serve as a quick reference for industry to determine pre-chatter conditions, so poor surface roughness can be avoided. Cutting condition values could be put in a formula to evaluate whether the cutting conditions would produce a chatter-free workpiece. Work in this area has already begun with the development of a knowledge-based system for the prediction of surface roughness in turning process (Abburi & Dixit, 2006). This would eliminate guesswork by optimizing cutting parameters and controlling the quality required for desired surface finishes.

This study attempted unsuccessfully to find existing literary evidence of unsupported workpiece extension length/diameter ratio studies, where the surface roughness values were equivalent to those of supported turning. In addition to the past research conducted in this area, the researcher sought out experts explicitly involved with work utilizing lathe applications. An interview with the first expert, who specialized in tooling applications, revealed no knowledge of previous formulas for determining the unsupported workpiece extension length/diameter ratio in turning operations. He cited a rule of thumb of "3-5:1" (3 to 5 inches length in ratio to every 1 inch in workpiece diameter) for a straight cut (Kennametal Inc., personal communication, October 10, 2005).

The second interview was with a highly experienced engineer who was involved in the design of "Steady Rests". A rule of thumb that specified approximately "7-10:1" was given as their guideline for an unsupported workpiece extension length/diameter ratio (Arobotech Systems, Inc., personal communication, December 16, 2005).

The third interview was with a setup man in a job shop, whose area of expertise was lathe work. He gave an estimate of 1:4, which he felt would be appropriate for a straight cut, using low carbon steel. When asked about the unsupported workpiece extension length/diameter ratio reference chart, he said he felt there was a definite need for this type of reference in industry because of the amount of trial and error necessary to optimize the machining process (Western Machine Tool & Die, personal communication, December 20, 2005).

The fourth interview was with an executive of manufacturing operations. He was also unaware of such a formula and stated "The lack of a formal procedure was a problem, especially for the new machinists who had no past experience with which to base a judgment call on." He felt there was a very real need to establish some form of reference material relevant to the unsupported workpiece extension length/diameter ratio (Kelm Accubar, personal communication, December 28, 2005). Although there is no clear agreement on what an appropriate ratio should be, there is consensus as to the need for such a standard.

Purpose of the Study
The purpose of this study is to identify a region along the length of the workpiece where the surface roughness values of the unsupported workpiece were statistically comparable to those of the supported workpiece. A reference chart was then developed to illustrate where an operator could forego the use of the tailstock during setups. This chart, like the commonly used feed rate, spindle speed, and depth of cut charts, would serve as a reference to operators who routinely perform lathe setups to eliminate uncertainty in the setup procedure, minimize required setup time, maximize setup and operational efficiency, and reduce overall operating costs.

Methodology
An experimental design was created to test the resultant surface roughness of varying workpiece extension length/diameter ratios in a straight turning

process. The experiments, involving seven different workpiece lengths and only on the diameter of 1", focused on a straight cut of a half inch that was made from the end of each workpiece. The resultant surface roughness was measured for each of the test increments. The surface roughness values reflected the difference in surface finish as the workpiece extension length to diameter ratio changed. Since previously published research on this specific subject is very limited, the results of the study were based on empirical evidence obtained during the course of the experiments performed during this research. This research project was designed to address the issue in a general manner, focusing on straight turning of low carbon steel using a finishing cut. The experiment was carried out in a setting which closely replicated an actual manufacturing facility. The research laboratory used is situated in the College of Engineering, Department of Technology, Manufacturing Processes Laboratory, at Southern Illinois University Carbondale. The SIUC laboratory equipment chosen for use in the experimental process are all commonly available at industrial manufacturing suppliers. They include the following:

- Bridgeport EZPATH SD CNC Lathe (ROHM No. P5354 three jaw chuck)
- Brown & Sharpe Pocket Surf Surface Roughness Tester, Range: R_a - 1µ" to 250µ"
- Brooks Rockwell Hardness Tester
- Kennametal Tool Holder: Part No. MCLNR-124B (Right Hand Tool Holder – Combination lock pin and top clamp)
- Kennametal Coated Carbide Inserts: Part No. CNMG 432 FN, Grade 9125
- Kool Mist Formula No. 78 (Synthetic Coolant Concentrate)
- 1018 Cold Rolled, Low Carbon Steel: 1" diameter

Due to the differing opinions among industry professionals about a common workpiece extension length/diameter ratio (Kennametal Inc., 2005; Arobotech Systems, Inc., 2005; Western Machine Tool & Die, 2005; and Accubar, 2005), various workpiece exten-

sion lengths that would encompass all currently examined industry guidelines from one extreme to the other, and beyond, were tested. This research challenged the traditionally accepted boundaries by exceeding the previous maximum workpiece extension length/diameter ratio of 10:1 to nearly double that figure, by using a ratio of up to 19:1 in the experiments. The reason for using this approach was to find the safe limit of process functionality for a given workpiece diameter. However, attempts to effectively machine an unsupported workpiece in the range of 17:1 to 19:1 resulted in severe workpiece deflection which rendered the cutting action of the insert ineffective, leaving a surface of pronounced chatter. Attempts to machine workpiece material in the range of 7:1 to 15:1, resulted in fractured cutting inserts. Finally, workpiece surface roughness produced in the range from 4.5:1 to 6.5 exhibited extreme chatter that at one point was beyond the operating range of the surface roughness tester. Since the early experimental trials illustrated a lack of machinability in these workpiece extension ranges, this research focused on what was determined to be the effective cutting range of this particular material, of 1:1 to 4:1.

Therefore, a series of workpiece extension lengths which include the following 1", 1 ½", 2", 2 ½", 3", 3 ½", and 4" served as the *treatments* or independent variables. In Figure 1, an unsupported workpiece is shown and the various workpiece lengths and ratios are illustrated by the lines spaced every half inch.

The experiment consisted of the previously mentioned group of workpiece lengths that were chucked in the lathe and turned one-half inch from the unsupported bar end using a straight cut. Also noted is the uniform length of workpiece material of two inches that was clamped in the chuck for each of the seven trials.

In order to verify differences in surface roughness measurements between the supported and unsupported workpieces, it was necessary to examine trial results
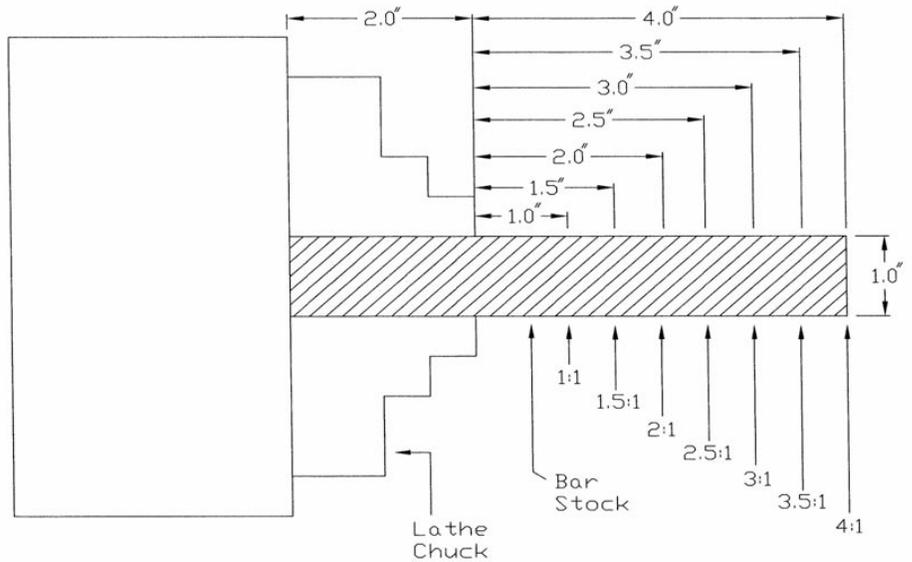
Figure 1. Illustration of workpiece extension length/diameter ratios

from a group of supported workpieces as well. The experiment was repeated as previously stated, with the exception of the use of a tailstock as a means of workpiece support. The use of a tailstock with a live center for workpiece support is the typical method in which turning operations are performed. Therefore, this method was used to establish a control condition with which to determine the statistical significance of the experimental results. Test values for both the supported and unsupported trials were evaluated for statistical significance.

Procedure

An approach that focused on common applications was used. For the initial research, it was important to select a material that would be applicable to a broad range of manufacturing applications so as to have the greatest benefit to industry. A description of the steps necessary to perform the study was developed. They are as follows:

Material Selection and Preparation

As noted, 1018 cold rolled, low carbon steel was used for the workpiece material. This particular material, while not representative of all workpiece materials, was chosen specifically because of its wide-spread use in industry,

and also because it would be beyond the scope of this research to involve all materials at this level. The material was a standard 1" diameter cold rolled unmachined bar. The bar stock consisted of 20 individual pieces, each being 6" in length. The additional two inches in length allowed for chucking of the bar stock. The seven different bar lengths, as illustrated in Figure 1, were tested by machining 10 pieces at each length unsupported as the treatment and 10 pieces at each length supported by means of a tailstock for establishing the control condition. The control condition (supported) surface roughness represents a comparison against which the experimental (unsupported) surface roughness was compared.

Operating Parameters

Next, the operating parameters for the lathe and tooling were identified using the Kennametal Lathe Tooling Catalog 1010 (2001). This step referenced existing knowledge of turning operations to optimize the cutting process, with guidelines specific to this material and tooling application. The guidelines listed were as follows:
The insert chosen for this research was the CNMG432FN Grade KC9125. It is a TiN coated carbide insert that is designed for finishing cuts and has a

negative rake geometry. Its shape is diamond with 80^0 nose angle and a 7^0 relief angle. Using the Kennametal Insert Selection Guide, which illustrates how to choose the correct machining specifications for a given application, the chosen parameters were depth of cut 0.035 inch, with a feed rate of 0.10 inch per revolution. These two criterions were chosen because they represent average insert usage as represented in the guide. However, for this particular research application, the surface feet per minute rate, or cutting speed, as listed in the Kennametal guide proved to be too high, which resulted in extreme chatter and tool breakage. The Machinery's Handbook 25 (1996) was also consulted for appropriate machining parameters with regard to surface feet per minute. The data from their table was similar to that of Kennametal. However, the text stated "Although the accompanying tables provide recommended cutting speeds and feeds for many materials, experience in machining a certain material may form the best basis for adjusting the given cutting speeds to a particular job" (Industrial Press, Inc. 1996, p. 977). So, by evaluating the surface roughness characteristics to find a point at which tool breakage had been eliminated and the workpiece was free of chatter, the maximum surface feet per minute rate of 327 was determined to be the best rate for our experiment. Therefore, the surface feet per minute rate was revised for use in this research. The machine RPM was 1250.

Material Processing

There were two ten bar sets. One set was labeled E to represent the experimental set and the other labeled C for the control set. One new insert was used to process the experimental set and one new insert was used to process the control set. This was done in order to eliminate tool wear as a factor in the final surface roughness analysis. The unsupported bars were chucked precisely two inches from the labeled end by aligning the chuck jaw with a mark on the workpiece. The supported bars were placed securely by hand against the tailstock, which had

been positioned to act as a stop to also allow exactly two inches of the bar to be chucked. The lathe was then programmed, using the aforementioned machining parameters, to machine the last half inch of material from the end of the bar. All ten bars in the respective set being processed (experimental or control) were machined consecutively at the particular bar length being evaluated (ex: 4"; 3.5"; 3"; 2.5"; 2"; 1.5"; or 1") and then measured for surface roughness. Next, the machined sections of each bar in the set were cut off on the lathe and the experiment repeated at the new bar length, one-half inch shorter than before. This procedure provided 10 samples at each bar length and was repeated until all seven of the prescribed lengths had been machined and recorded for each of the respective sets. The hardness of each of the 20 bars was also checked, on an unmachined surface. The measurements were obtained by using a Brooks Hardness Tester. The Rockwell "B" scale was used to perform the tests. The tests revealed a very uniform hardness, ranging only from 93 to 95, throughout all of the specimens. This eliminated inconsistency of hardness as a factor related to the surface roughness results.

Measurement process

To take measurements in a consistent manner that eliminated machine and human error, the measuring process was examined for inconsistencies. The

Brown & Sharp test equipment required no calibration before each measurement. However, to eliminate human error as a factor, the workpiece and tester were set up in a manner that standardized the process, allowing for a hands-off technique. The measuring process for surface roughness consisted of first placing each workpiece sample in a vise. Then, using the B&S Pocket Surf surface roughness tester which was attached to a base unit, taking three separate measurements visually spaced approximately 120^0 apart around the perimeter of the bar on the machined surface. This was to insure accuracy of the readings by averaging the natural variations of the surface roughness values.

Findings

The surface roughness values for each of the 10 length values for both sets were arranged and are reflected graphically in Figure 2.

The differences between average surface roughness values for the supported and unsupported workpiece treatments were then statistically analyzed using a t-test. Using a critical α level of .05, a Two-Sample t-test (Assuming Unequal Variances) statistical evaluation was performed to test for a significance level between the supported and unsupported workpiece experimental results. Additionally, the final analysis included the use of descriptive statistics for construction of a graph, for a visual representa-

Figure 2. Comparison of Surface Roughness Mean Values
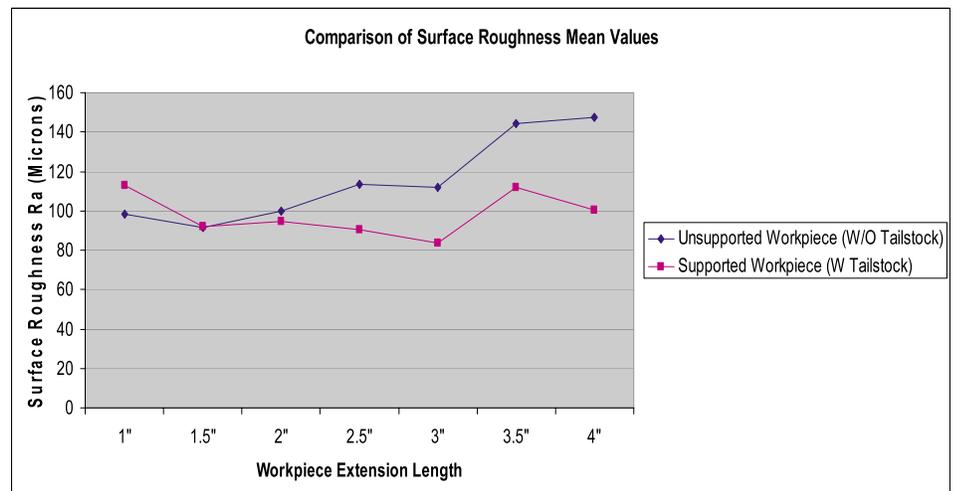
tion of the results. The results from this test are summarized in Table 1. (Note: Su = Supported; Un = Unsupported)

Two particular trends appear in the graph, one expected and the other rather unexpected. As expected, as the workpiece extension length gets progressively longer, the mean chart values for the unsupported workpiece begin to move in an upward trajectory, suggesting an increasing instability within the system as expected. Surprisingly however, the pattern suggests that at distances of less than 1.5", an undesirable element leading to system instability has been introduced to the supported workpiece. This indicates stability issues, possibly linked to the cutting tool's proximity with the lathe chuck.

Conclusions

Although this plan looks only at the relationship of one diameter of bar stock in varying lengths, the results validate the original premise of equal surface roughness in some regions of workpiece length when comparing supported and unsupported turning and have been used to develop a reference chart that defines the boundary in question. The results illustrated in Table 1, show statistically significant differences in surface roughness at workpiece extension length/diameter ratios of 1:1, 2.5:1, 3:1, 3.5:1, and 4:1. This leaves the ratios of 1.5:1 to 2:1 as the region where workpiece support played an insignificant role in surface roughness for workpieces of 1" in diameter. However, even though the 1:1 ratio was statistically significant, the unsupported method produced superior surface roughness values at this length. So, the applicable range of workpiece extension lengths can be safely extended from 1:1 to 2:1 without loss of product surface finish quality.

The development of the reference chart included regions that were labeled to represent workpiece extension length/ diameter ratios which are acceptable and unacceptable respectively. The acceptable regions represent areas able to produce surface roughness values equivalent to a supported turning opera-

Table 1. t-Test: Two-Sample Assuming Unequal Variances

Analysis Results of Test Data

Pair	Sample		t-Statistic	T Critical two-tail	Significance
Pair 1	1"	Su/Un	-3.046	2.119	Significant
Pair 2	1.5"	Su/Un	0.077	2.144	Insignificant
Pair 3	2"	Su/Un	1.421	2.109	Insignificant
Pair 4	2.5"	Su/Un	6.065	2.178	Significant
Pair 5	3"	Su/Un	13.557	2.200	Significant
Pair 6	3.5"	Su/Un	4.010	2.100	Significant
Pair 7	4"	Su/Un	5.831	2.200	Significant

tion. The unacceptable regions represent areas that will produce surface roughness values that are inferior to typical supported turning operations. Table 2 illustrates an abbreviated Unsupported Workpiece Comparison Chart.

Implications

The method used in this work can be effectively expanded, through additional research, over a wide range of workpiece diameters, lengths, and materials. Comprehensive data can be compiled to develop a series of charts which can be used to eliminate an element of setup waste related to turning operations within the manufacturing industry.

Recommendations

This study has addressed an area that has been largely neglected in the past. Now that the initial research has now been conducted for this specific topic, surface roughness equivalencies of the supported vs unsupported workpiece, a methodology is available to those who wish to continue with this effort. Future work should include studies that

explore the following:
• Different workpiece diameters
• Different workpiece materials
• Larger sample sizes
• Further detailed examination at turning lengths from 1-1.5"

Using the same workpiece material, the chart can be broadened to include a wide range of diameters and lengths applicable to this particular material. An example of one possible configuration is the Future Unsupported Workpiece Reference Chart, illustrated in Table 3.

Further testing, beginning with the 2" and 3" diameter intervals, may be enough to reveal a pattern where prediction becomes possible through means of a model which uses an algorithm to create a viable chart without physically performing "hands-on" testing at each individual increment.

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Table 2. Unsupported Workpiece Comparison Table

Range of Acceptable / Unacceptable Regions for: 1018 Cold Rolled Steel

Diameter		Lengths	
	Acceptable		Unacceptable
1"	1" - 1.5" - 2"		2.5" - 3" - 3.5" - 4"

Table 3. Future Unsupported Workpiece Reference Table

Range of Acceptable / Unacceptable Regions

Diameter	Lengths										
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
.5											
.75											
1.0	A	A	A	U	U	U	U	U	U	U	U
1.25											
1.5											
1.75											
2.0											
2.25											
2.5											
2.75											
3.0											

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