Journal of Manufacturing Processes
Vol. 4/No. 2
2002

The Effects of Corner Radius and Edge Radius on Tool Flank Wear

William J. Endres, Dept. of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, Michigan, USA
Raja K. Kountanya, Dept. of Mechanical Engineering, University of Michigan, Ann Arbor, Michigan, USA

Abstract

The use of cutting tools with a honed edge radius to protect the cutting edge from chipping is ever increasing. The basic understanding of the fundamental cutting mechanics in the presence of an edge radius is increasing as well. The present state of knowledge leads one to question how edge-radiused tools behave under conditions that are more practical than straight-edged orthogonal cutting. Presented here is a study of the interaction of edge radius with corner radius, the latter of which is commonly seen in turning, boring, and face milling processes. Turning test data show that tool flank wear can be minimized for up-sharp tools by using a moderate corner radius. For tools with an edge radius, a wear-minimizing corner radius still exists but is higher than for up-sharp tools. Physical interpretations of these direct and interaction effects are presented.

Keywords: *Flank Wear, Orthogonal Cutting, Edge Radius, Hone, Machining Force, Turning*

Introduction

Applying a honed radius to a cutting edge to protect it from chipping is being increasingly employed to enhance tool life. However, it is known that cutting efficiency drops significantly when the uncut chip thickness drops below about two times the edge radius. Inefficient cutting increases mechanical and thermal loads per unit of material being removed. Therefore, when the uncut chip thickness is small, such as in hard machining and drilling, edge-chipping protection comes at the cost of increased temperatures, residual stresses, forces, deflections, and machine power. These facts are driving a need to better understand the pros and cons of using edge-radiused tools and how to appropriately size the edge radius to enhance the associated advantages.

Various studies in the 1960s (Albrecht 1961, Palmer and Yeo 1963, Connolly and Rubenstein 1968, Nakayama and Tamura 1968) began exploring the effects of the edge radius. Their efforts have been followed by numerous more-recent studies aimed primarily at modeling the process when an edge radius is present, using both analytical and semi-empirical methods (Endres, DeVor, Kapoor 1995; Waldorf 1996; Manjunathaiah and Endres 2000; Schimmel, Endres, Stevenson 2002) and finite element methods (Marusich and Ortiz 1994; Chen 1999; Madhavan, Chandrasekar, Farris 2000; Movaheddy, Gadala, Altintas 2000). Building on the aforementioned early efforts, some recent works have taken a step back to basic orthogonal cutting experiments toward improving the understanding of how edge radius and other tool geometry affect cutting performance (Schimmel, Endres, Stevenson 2000, 2002; Kountanya and Endres 2001) to ultimately support further and improved modeling.

While there is still much to learn about the basic effects of the edge radius through continuing orthogonal cutting studies, there is one generally well-documented fact. That is, cutting becomes less efficient, or exhibits higher specific energy, when the ratio of the uncut chip thickness to edge radius decreases. As noted earlier, this leads to higher thermal loads on the cutting edge.

Uncut chip thickness is primarily driven by feed rate. However, the corner radius* employed in many processes also affects the uncut chip thickness (see *Figure 1*). For this tooth geometry, the uncut chip thickness reduces along the corner radius and ultimately approaches zero near the tip of the tool. If an edge radius is applied to protect the cutting edge from chipping, the corner radius portion, in particular near the tool tip, is subjected to a reduced cutting efficiency. An increase in corner

---

This paper is an original work and has not been previously published except in the *Transactions of NAMRI/SME,* Vol. 30, 2002.

*Corner radius is the radius blending the major (lead) and minor edges of the tooth profile whereas the edge radius is the radius that blends the rake and flank faces and is the location at which the work material separates to form the chip and the machined surface.

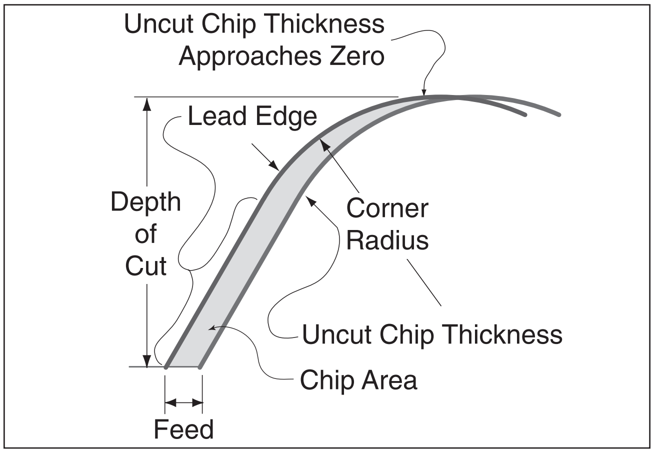

Figure 1
Tooth Geometry and Uncut Chip Thickness Variation for Corner-Radiused Tools

radius further reduces the uncut chip thickness, making cutting near the tool tip even less efficient, presumably increasing temperature and tool wear.

On the other hand, it is well known that tools with a near-zero corner radius (sharp-cornered tools, see *Figure 2*) often exhibit an increase in wear that is concentrated near the sharp corner. For example, this is commonly seen at the outer diameter of end mills and drills (compounded by increased local cutting speed as well in the latter case). Therefore, one might hypothesize that an increase in corner radius could serve to spread the overall thermal load across a greater region of the cutting tooth, providing a better heat conduction path to the bulk of the tooth, potentially lowering the temperature along the cutting edge and reducing wear.

The research reported here explores the main and interaction effects of corner radius and edge radius on flank wear. The results show that the aforementioned hypothesis proves true; that is, applying a corner radius does improve flank wear relative to that of a sharp-cornered tool. Furthermore, data acquired for edge-radiused tools show a substantial coupling, or interaction effect, between corner radius and edge radius.

Effect of Corner Radius—Up-Sharp Tools

Experiment Setup

The workpiece material is AISI 1040 steel barstock with a hardness of 58.5 – 61.3 HRA. A standard CTEPR 864E tool holder having a 30 deg lead angle is used for all tests. The inserts are up-sharp (approximately 5-10 μm edge radius), uncoated, and of Kennametal plain carbide grade K68 (ISO C3).† A TPG 43_ geometry is used where the last entry represents the corner radius. Four levels of corner radius—0.2, 0.8, 1.2, and 1.6 mm, which correspond to numbers 0.5, 2, 3, and 4—are used in the test plan. The 0.2 mm corner radius is intended to approximate a sharp corner, alleviating the need to modify a commercially produced tool by grinding away the corner radius, which could unknowingly alter the tool in other ways.

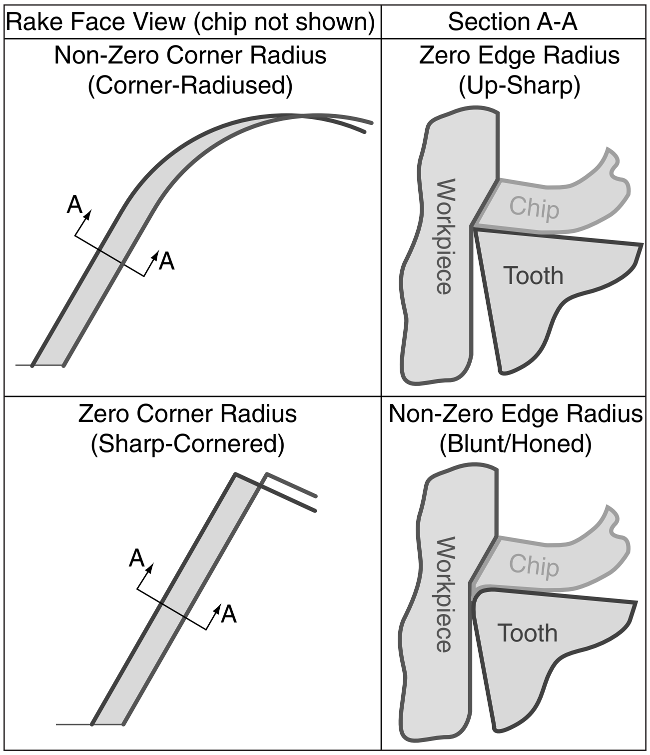

Figure 2
Clarification of Edge Radius and Corner Radius, Sharp or Not

Tests are conducted at three feeds: 0.022, 0.037, and 0.083 mm/rev. These are relatively small feeds, but are in line with those used in finish cuts and in gun drilling of steels (an initial motivator of the effort). Each combination of feed and corner radius yields 12 tests, which are then repeated three times, using the three edges of the same triangular insert, for a total of 36 wear tests. All tests are performed at 3.05 m/s (183 m/min.) for a three-minute duration. The depth of cut is chosen to be 2.5 mm, making it at least three times the depth at which the lead edge tran-

---

†Improved gun-drill design was the initial motivator of this research. This grade was chosen since a more logical choice of C5 or C6 is not applicable in gun drills at the current state of their technology.

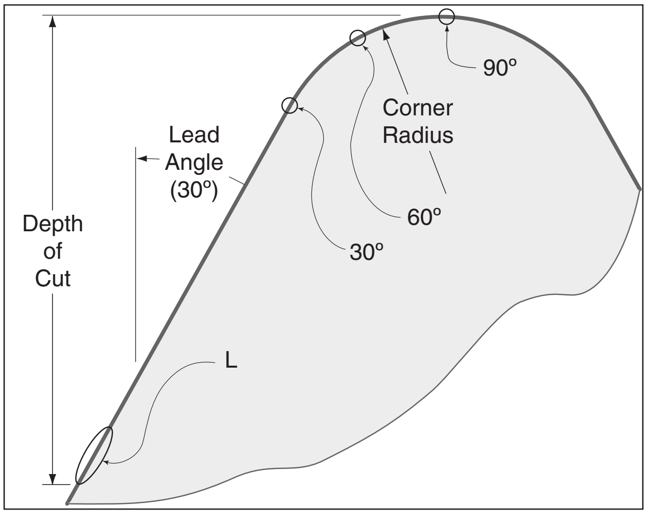

Figure 3
Edge Radius and Wear Measurement Positions

sitions into the corner radius ($d_t = r_\varepsilon \sin\psi_r$, so that $3d_t = 3\cdot1.6\cdot\sin30° = 2.4$ mm) for all corner radii. This transition point is noted as the 30° point in *Figure 3*; *Figure 3* indicates the locations at which wear and/or edge radius measurements are made.

Wear Results

After each cut, the insert is washed in concentrated HNO_3 to remove any adhering build-up, though in most cases no build-up is observed. Flank wear is measured on an optical microscope. Measurements are recorded as an average of three measurements at the general location on the lead edge beyond (into the cut) the depth of cut notch, and a single measurement at the tool tip—the 90° point shown in *Figure 3*. These two measurement locations are referred to as "lead-edge" and "corner-edge," respectively. *Figure 4* shows a sample image taken from the lead edge. The image confirms that the damage to the cutting edge is traditional flank wear and not chipping.

Wear is graphed in *Figure 5* versus corner radius for each of the three feeds. The lead-edge data show very good consistency across the three repetitions. Generally speaking, there is more scatter in the corner-edge measurements at each condition. This is probably a result of having a narrow field of focus when viewing the rounded tool tip from the flank perspective. Another possible cause is that the tool tip exhibits increased sensitivity to edge anomalies that become large at the tool tip when considered relative to the reducing uncut chip thickness. Specific anomalies include grind marks and natural variation of the edge within the nominal 5-10 µm up-sharp range.

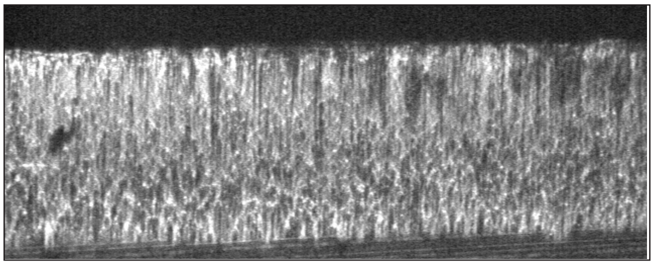

Figure 4
Flank Wear Land Indicates No Chipping, that is, Traditional Flank Wear

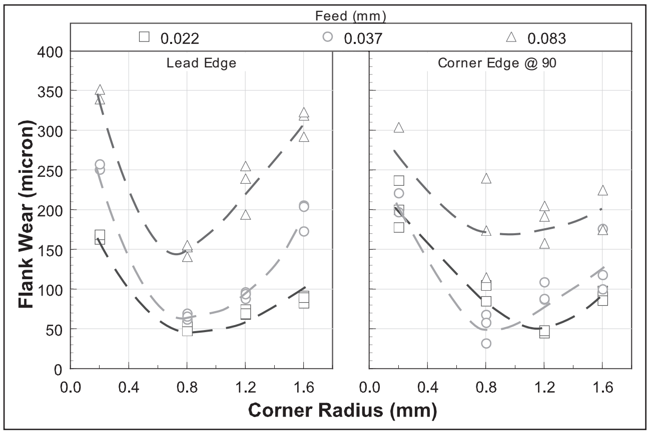

Figure 5
Lead-Edge and Corner-Edge Wear vs. Corner Radius for Up-Sharp Tools

Based on *Figure 5*, there is clearly a corner radius greater than the minimum considered (0.2 mm) at which wear is minimized. The lead-edge wear exhibits its minimum at a corner radius somewhere between 0.2 and 0.8 mm. The corner-edge wear shows a minimum at a slightly larger corner radius, in particular for the lowest feed. This result confirms the hypothesis that employing a corner-radiused tool as opposed to a sharp-cornered tool will reduce wear. However, this is true only to a point, in that even larger corner radii then begin to worsen the wear rate. This means that at some point the detrimental effect of increased specific energy that comes with added chip thinning (via increased corner radius), through the associated size effect (small uncut chip thickness relative to edge radius, among other effects), outweighs the advantage of the thermal load distribution effect.

The corner-edge wear is minimized at a larger corner radius than is the lead-edge wear, in particular for the lowest feed. This may indicate that the thermal load distribution effect is stronger local to the corner radius, while the lead-edge wear, though benefiting to some degree from the thermal load distribution effect, is more strongly dominated by the overall thermal load. In other words, the thermal load distribution effect of corner radius has a direct (local) effect on the corner-edge wear and an indirect (global) effect on the lead-edge wear.

From *Figure 5* it also appears that wear is less sensitive to feed at corner radii close to that which minimizes lead-edge wear, that is, the lower feed curves are flatter. A more evident observation is that the effect of feed on corner-edge wear is smaller than that on lead-edge wear, that is, the trend lines are flatter in the corner-edge wear plot as compared to the lead-edge wear plot. Because the local uncut chip thickness at the tool tip is not strongly affected by feed, while that on the lead edge is proportional to feed, this makes sense. To expand on the conclusion earlier about corner radius and its local and global thermal load distribution effects, one can think of the feed as having a more direct (local) effect on the lead-edge wear and a weaker indirect (global) effect on the corner-edge wear.

It should be noted that the effect of depth of cut is not studied here. Further studies of its effect, and potential normalization of that effect with respect to corner radius, may be of interest. This study is intended to assess differences when depth of cut is held constant at a level that is large relative to the corner radius. It is conceivable that when the depth of cut is smaller, around the corner-lead transition depth (d_t, at the 30° point here), that the lead-edge wear characteristics would be more in line with the corner-edge wear characteristics. This is so because the corner radius and its stronger localized thermal load distribution benefits would now become more "localized" relative to the entire edge in the cut, not just the tool tip.

Furthermore, it would be expected that these trends would continue to exist when feeds get higher, at least to a point. That is, when feeds get large relative to the corner radius, say greater than one-half the corner radius, the chip geometry "proportions" change, which may likely change the trends seen here. However, typical applications of corner-radiused tools do not employ feeds that large relative to the corner radius, so these results should be quite practically applicable.

Machining Force Results

The three machining force components—cutting, feed, and depth—are recorded at a 1000 Hz sampling rate for the duration of the cut, including the occasional brief interruptions needed to move the tool back to the other end of the workpiece. These interruptions occur only on rare occasions. Based on the findings of Stern and Pellini (1993) that show cooling to mainly affect crater wear with little effect on flank wear, any tool-cooling effect here is considered negligible. Forces at the start and end of the cut are of interest to see what effect the corner radius might have on forces in the fresh tool state, and how the changes in wear across corner radii and feed rate translate into changes in force from the start to the end of the cut.

The corner radius is found to have little effect on the fresh-tool cutting force and only a slight effect on the equivalent thrust force, the latter of which is the resultant of the feed and depth force components. To make sense of this result, consider the often-used force modeling approach that calculates the cutting and equivalent thrust forces to be

$$F_\bullet = u_\bullet a, u_\bullet = u_{c_\bullet} h^{b_{h\bullet}}, \bullet = C, T, \tag{1}$$

where a is the chip area, the product of the feed f and depth of cut d (ignoring the negligible "cusp" area at the corner radius intersection), $u_{c_\bullet}$ is a constant, and $u_\bullet$ is the specific energy for the cutting ($\bullet = C$) or thrust ($\bullet = T$) direction. The power law in terms of uncut chip thickness h is the mathematical representation of the size effect. For corner-radiused tools, it is customary to use the average uncut chip thickness, $\bar{h} = a / w$, where w is the equivalent width of cut—the length of the cutting edge that is in contact with the work material.

Typical values of the exponent $b_{h_\bullet}$ are -0.3 for the cutting direction and -0.6 for the thrust direction. Based on these typical values, using Eq. (1) and the related geometry equations (e.g., Endres and Waldorf 1994) that introduce the effect of corner radius on $\bar{h}$, one would expect force to increase only about 8% and 17% in the cutting and thrust directions, respectively, from the smallest to the largest corner radius considered here. Such a small effect is a result of the depth of cut being large relative to the corner radius, which

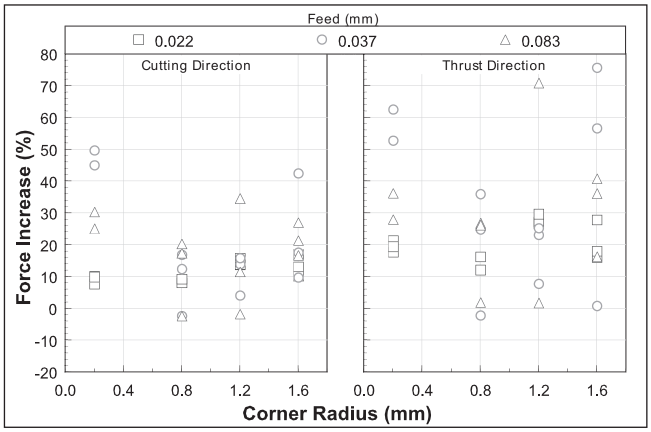

Figure 6
Force Increase at End of Cut (Worn Tool) Relative to Start of Cut (Fresh Tool)

causes the average uncut chip thickness to be dominated by the feed with only a small effect of corner radius. These levels of increase are consistent with the small increases seen here across corner radii.

The percent increase in force at the end of the cut, relative to the fresh-tool forces, tends to show more scatter at each combination of conditions (see *Figure 6*). Because both the fresh-tool forces and the wear measurements shown in *Figure 5* are quite repeatable (low scatter for each combination of conditions), it is solely the scatter in worn-tool forces that is responsible for the scatter seen in the force increases displayed in *Figure 6*. In the few combinations of conditions that show extremely large scatter, there is some evidence of chipping on the edge; other cases may be related to build-up on the tool. Typically, the worn-tool forces are higher, although there are a few tests that show a decrease (negative values in *Figure 6*), which is attributed to experimental error.

One general trend is that the thrust force is more strongly affected by wear, which has been documented in numerous past studies (Elanayar and Shin 1996; Taraman, Swando, Yamauchi 1974). Another general trend, keeping in mind that lower feeds exhibit lower wear, is that the higher feed tests are less affected by (their higher) wear. This makes sense because the force attributable to the wear land is smaller at higher feeds when considered as a percentage of the fresh-tool forces, which are largest for the highest feed. Finally, there is some trend with corner radius, with the force-increase tending to be lower around the 0.8 mm corner radius, which is simply a result of those tools showing the lowest wear in *Figure 5*.

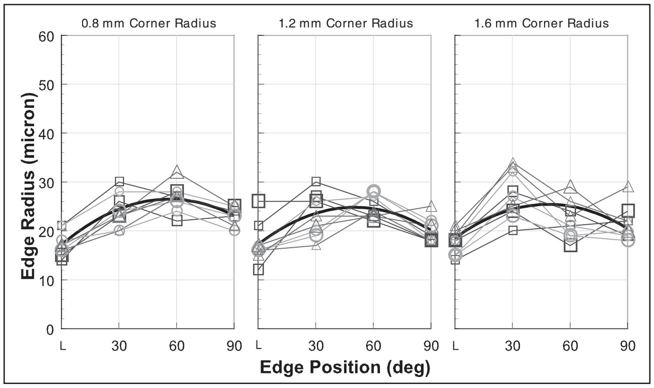

Figure 7
Edge Radius Variation with Edge Position for Small-Hone Tools

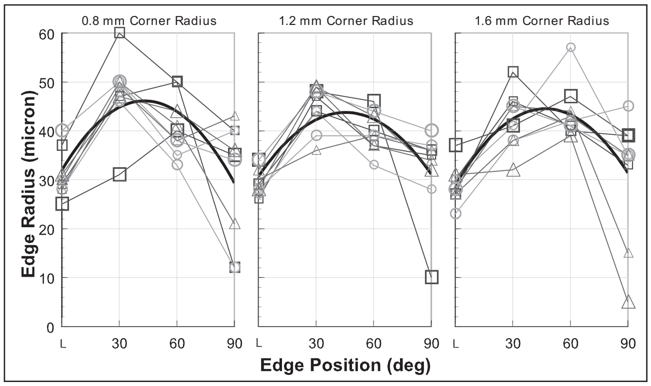

Figure 8
Edge Radius Variation with Edge Position for Large-Hone Tools

Interaction of Corner Radius and Edge Radius

Given the finding that corner radius does, to a point, spread the thermal load across the tooth to reduce wear, how does that advantage fare when an edge radius is applied, knowing that it will exacerbate the negative aspects associated with size effect along the corner radius? To answer this question, two levels of edge radius, "small" and "large," are compared across the four corner radii.

Edge Radius Measurements

All honed tools are measured on a Wyko white-light interferometry instrument and processed to estimate the edge radius at each of the four measurement points shown in *Figure 2*; Schimmel, Manjunathanaiah, and Endres (2000) described these methods in detail. For the smallest (0.2 mm) corner radius, because it is impractical to measure the edge radius around such a small corner radius, only the lead-edge measurement is made. All three corners (used for three repetitions) on three inserts (used for the three feed rates) for each of the four corner radius levels provide a total of nine measurements at each edge position for each corner radius. Results for the three larger corner radii are shown in *Figures 7* and *8*, where the "*L*" position is the lead-edge position near the depth of cut and is actually further up the cutting edge (in edge/arc length) from the 30° position than the horizontal axes of the plots suggest.

Each plot includes a heavy black curve, which is a least-square error quadratic fit to the data of all edges for that corner radius. Due to the noticeable noise in the data, the correlation coefficients are quite low (0.3-0.5); these curves are intended only to give a visual summary of the general trend of all the tools together. The large amount of noise in the data, based on our numerous experiences measuring edge radius, is typical as the measurements are often plagued by grind marks, especially for these low levels of edge radius (compared to large honed edge radii that can be as high as 150 μm in practical applications). This study is yet one more motivator for finding a better way to measure edge radius, perhaps with a less general instrument that is specifically tailored to measuring a cutting edge and the filtering of grind mark effects.

Small-Hone Tools

The small-hone tools were requested to have a nominal 25 μm edge radius. *Figure 7* shows the maximum edge radius to occur around the 45° point and to be about 20-30 μm—centered on the 25 μm target. However, just slightly (relative to the overall length of the lead edge) up the lead edge, the edge radius drops by about 30-40%. These results are consistent with the observations of Schimmel, Manjunathanaiah, and Endres (2000) where the edge radius on the tool tip closely matches the target value while the edge radius along the lead edge decreases significantly.

Large-Hone Tools

The large-hone tools have about a 45 μm edge radius at the 45° point, decreasing to about 25 μm on the lead edge, as shown in *Figure 8*. These data tend to show even more noise. We have no physical explanation why the larger edge radii would exhibit greater effects of grind marks except that their base up-sharp inserts were from a different batch than were the small-hone inserts; however, they were from the same batch as the up-sharp inserts discussed earlier. The pattern in which the edge radius is smaller on the lead edge and larger around the 45° point is consistent with the other batch. From this and previous studies, we conclude that this parabolic pattern is a natural characteristic of the commercial brush honing process.

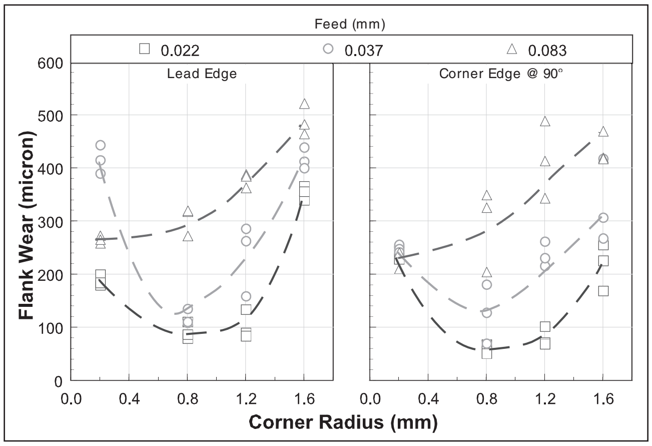

Figure 9
Flank Wear vs. Corner Radius for Small-Hone Tools

Wear Results

Small-Hone Tools

The wear measurements for the small-hone tools are shown in *Figure 9*. Like for the up-sharp tools, there is again a corner radius that minimizes wear, at least for the lower feeds. For the highest feed, wear tends to increase with corner radius; perhaps there is a minimum between the 0.2 and 0.8 mm corner radii. All wear levels are higher than for the up-sharp tools just as they should be due to the presence of a sizable edge radius, which decreases cutting efficiency and subsequently increases temperature and wear rate. Like for the up-sharp tools, wear tends to be lower at the tool tip than on the lead edge.

Large-Hone Tools

The wear on the large-hone tools is shown in *Figure 10* in comparison to the small-hone wear measurements. For the larger edge radii, one would expect a reduced cutting efficiency and a subsequent increase in temperature and wear rate. Given that expectation, the large-hone data appear inconsistent with wear levels being higher at some corner radii and lower at others. Apparently it is not that simple.

Another view of the data is shown in *Figure 11* where trend curves have been added to highlight an alternate perspective. That is, other than at the lowest corner radius, wear does decrease with an increase in corner radius, most dramatically and quickly for the lowest feed. From this perspective, because the wear cannot continually decrease, it

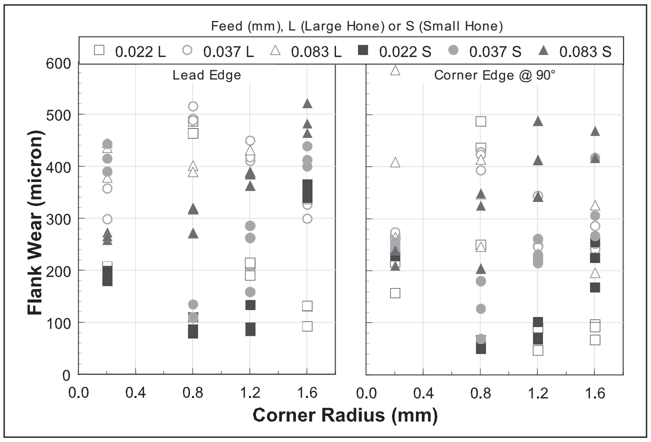

Figure 10
Comparison of Flank Wear vs. Corner Radius for Large and Small-Hone Tools

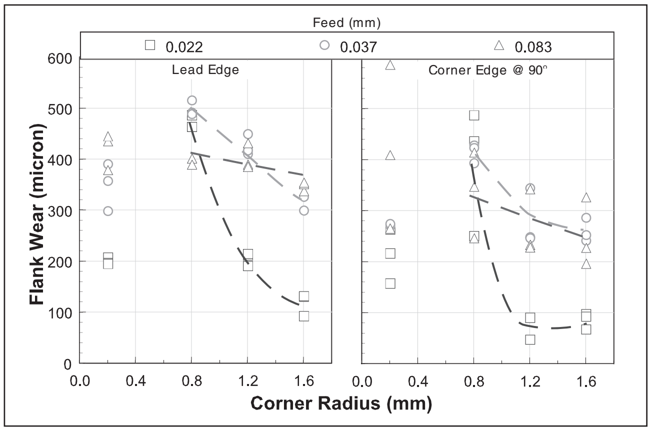

Figure 11
Flank Wear vs. Corner Radius for Large-Hone Tools

either asymptotically reaches some level as corner radius continues to increase, or there must be a corner radius beyond the range studied that will minimize wear. In either case, these data motivate one to accompany a larger edge radius with a larger corner radius in order to decrease wear. From a physical point of view, the data demonstrate that the higher thermal loads that come from reduced cutting efficiency at higher edge radii require a larger corner radius to effectively provide the thermal load distribution effect seen for the up-sharp tools.

Regarding the smallest corner radius, one must note that its edge radius is lower (similar in size to that on the lead edge for the other corner radii) over almost the entire edge, unlike the larger corner radii that exhibit an increased edge radius along the corner radius—a substantial portion of the edge. This may explain why the wear levels for the 0.2 mm corner radius are lower than at the larger 0.8 mm corner radius. Nevertheless, what is most important is that the wear levels at the largest corner radius studied are indeed less than or tending to be less than those at the 0.2 mm corner radius, indicating that wear is in fact improved compared to the sharp-corner option.

Wear Results Summary

One positive note is that there is one consistency across all tools, honed or otherwise—wear levels on both the lead and corner edges are most sensitive to corner radius at the lowest feed.

Based on these results and the associated discussion, there is clearly an interaction effect of corner radius and edge radius. As the edge radius gets larger, a larger corner radius is needed. This suggests that the increased thermal load that comes from lower uncut chip thickness to edge radius ratios for larger edge radii requires a larger corner radius to effectively distribute the increased thermal load to the point where wear begins reducing. Presumably, like the up-sharp tools, wear would eventually begin to increase at even larger corner radii where the chip thinning exacerbates the decreased ratio of uncut chip thickness to edge radius.

Machining Force Results

There is little more to say about the honed tool forces beyond the earlier comments regarding the up-sharp tool forces. Like for the up-sharp tools, the corner radius has only a minimal effect on the fresh-tool forces. In comparing the various levels of edge radius, there is a clear increase in force with edge radius level, especially in the thrust direction, as would be expected. The worn-tool force increases are again quite scattered.

Conclusions

The data presented here support the following conclusions regarding the interaction of corner radius and edge radius in their effects on process performance, measured in terms of tool flank wear and forces.

For up-sharp (unhoned) tools:

- There is a clear effect of corner radius on wear, with a corner radius of around 0.8 mm providing greatly reduced wear both at the lead edge and at the tool tip, and with lower feeds showing some shift of the wear-minimizing corner radius toward 1.2 mm.
- At corner radii close to the wear-minimizing corner radius, wear is less sensitive to feed as compared to other corner radii.

- In qualitative agreement with traditional modeling approaches, the increase in force components with corner radius (from 0.2 to 1.6 mm) is negligible in the cutting direction and only minor in the thrust direction.
- Typically, and as expected and shown in other studies, not only are the worn-tool forces higher than the fresh-tool forces, the percent increase is notably stronger in the thrust direction.

For the honed tools:

- The small-hone tools show a wear-minimizing corner radius around 0.8 mm, like for the up-sharp tools.
- The large-honed tools appear to show a wear-minimizing corner radius that is shifted to a higher level, less so for lower feeds and more so at the lead edge.
- Forces show similar trends as for the up-sharp tools, of course with higher thrust forces for the honed tools.

Based on these observations, the general conclusion is that an advantage exists in using a larger corner radius when using a larger edge radius.

Acknowledgments

The authors wish to express their thanks to various industry participants through their membership in the National Center for Manufacturing Sciences (NCMS) High-Throughput Hole Making consortium, which provided funding for this work to complement funding from NSF CAREER grant DMI-9734147. Specifically, we thank Jack McCabe of NCMS, who coordinated the consortium's effort, as well as the following individuals for their contributions of materials, tooling and measurement equipment: Frank Orteca and Mark McCollom of StarCutter Company, Dr. Jon Johnson of Ford Motor Company, Drs. Roy Schimmel, Anita Wiener, and Leonid Lev of General Motors Corporation, Mr. Bill Shaffer of Conicity Technologies, and Mr. Ray Moring of Kennametal, Inc.

References

Albrecht, P. (1960). "New developments in the theory of the metal-cutting process - Part I. The ploughing process in metal cutting." *ASME Journal of Engg. for Industry* (v82), pp348-358.

Chen, Y.R. (1999). "Drilling process modeling for new drilling process development." PhD thesis. Ann Arbor, MI: Univ. of Michigan.

Connolly, R. and Rubenstein, C. (1968). "The mechanics of continuous chip formation in orthogonal cutting." *Int'l Journal of Machine Tool Design and Research* (v8), pp159-187.

Elanayar, S. and Shin, Y.C. (1996). "Modeling of tool forces for worn tools: Flank wear effects." *ASME Journal of Mfg. Science and Engg.* (v118), pp359-366.

Endres, W.J.; DeVor, R.E.; and Kapoor, S.G. (1995). "A dual-mechanism approach to the prediction of machining forces: Part 1 - Model development, Part 2 - Calibration and validation." *ASME Journal of Engg. for Industry* (v117), pp526-541.

Kountanya, R. and Endres, W.J. (2001). "A high-magnification experimental study of orthogonal cutting with edge honed cutting tools." Paper #IMECE2001/MED-23317. *Proc.,* Symp. on Fundamental Issues in Machining.

Madhavan, V.; Chandrasekar, S.; and Farris, T.N. (2000). "Machining as an indentation process." *Journal of Applied Mechanics* (v67), pp128-139.

Manjunathaiah, J. and Endres, W.J. (2000). "A new model and analysis of orthogonal machining with an edge-radiused tool." *ASME Journal of Mfg. Science and Engg.* (v122), pp384-390.

Marusich, T.D. and Ortiz, M. (1994). "Finite element simulation of high speed machining." *Proc.*, Applied Mechanics Div., ASME IMECE, pp137-149.

Movaheddy, M.R.; Gadala, M.S.; and Altintas, Y. (2000). "Simulation of chip formation in orthogonal metal cutting process: An ALE finite element approach." *Journal of Machining Science and Technology* (v4), pp15-42.

Nakayama, K. and Tamura, K. (1968). "Size effect in metal cutting force." *ASME Journal of Engg. for Industry* (v90), pp119-126.

Palmer, W.B. and Yeo, R.C.K. (1963). "Metal flow near the tool point during orthogonal cutting with a blunt tool." *Proc.* of 4th Int'l MTDR Conf., pp61-71.

Schimmel, R.J.; Endres, W.J.; and Stevenson, R. (2000). "The application of an internally consistent material model to determine the effect of zero clearance in orthogonal machining." *Journal of Machining Science and Technology* (v4), pp101-125.

Schimmel, R.J.; Endres, W.J.; and Stevenson, R. (2002). "The application of an internally consistent material model to determine the effect of tool edge geometry in orthogonal machining." *ASME Journal of Mfg. Science and Engg.* (v124), pp536-543.

Schimmel, R.J.; Manjunathaiah, J.; and Endres, W.J. (2000). "Edge radius variability and force measurement considerations." *ASME Journal of Mfg. Science and Engg.* (v122), pp590-593.

Stern, E.L. and Pellini, R.P. (1993). "A study of the effect of tool wear on machining forces." *Proc.*, Mfg. Science and Engg., ASME-PED (v64), ASME IMECE, pp445-451.

Taraman, K.; Swando, R.; and Yamauchi, W. (1974). "Relationships between tool forces and flank wear." SME Technical Paper MR74-704, pp15.

Waldorf, D.J. (1996). "Shearing, ploughing and wear in orthogonal machining." PhD thesis. Urbana-Champaign, IL: Univ. of Illinois.

Authors' Biographies

Dr. William J. Endres is an associate professor in the Dept. of Mechanical Engineering-Engineering Mechanics at Michigan Technological University. He received his BS (1988), MS (1990), and PhD (1992) degrees in mechanical engineering from the University of Illinois at Urbana-Champaign. His research interests include machining dynamics, cutting mechanics, and mechanistic modeling techniques with an emphasis on the effects of edge bluntness, wear-land geometry, and other cutting tool geometry on the evolution of process performance, including dimensional accuracy, surface waviness (vibration), surface finish, residual stresses, and stability/chatter.

Mr. Raja K. Kountanya is a PhD candidate in the Dept. of Mechanical Engineering at the University of Michigan. He received his B.Tech (1996) in mechanical engineering from the Indian Institute of Technology (Madras) and MS (1998) in mechanics from Michigan State University; he expects to receive his PhD in 2002. His research interests include machining processes, materials issues in manufacturing, and plasticity.