CIRP Annals - Manufacturing Technology
Volume 59, Issue 1, 2010, Pages 215-218

Electro-erosion edge honing of cutting tools

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Abstract: Sink EDM of fine features necessitates the application of several tool electrodes to sequentially generate the required geometry, due to the inevitable localized wear of the tool that rapidly rounds-off sharp edges. Be that as it may, this phenomenon can be exploited to hone sharp edges of electrically conducting cutting tools by sinking the cutting edge into an appropriate counterface material. This paper presents the proof-of-concept and operating characteristics of this innovative process. Robust edge geometry generation, and a significant improvement in the life of high speed steel tools consequent to such preparation of the cutting edge are demonstrated.

Keywords: Cutting edge, Sinking EDM, Edge preparation

1. Introduction

Edge finishing is of critical importance in the function and performance of many engineering components: cutting tools in particular. Depending on the application, edges of tools used in machining operations typically involve a chamfer and/or a hone, on the order of several micrometers. The meso-geometry of the cutting edge has a profound influence on the mechanics of chip formation, with important implications on the integrity of the generated surface. The primary motivations for edge preparation are however to enhance the edge strength towards precluding the incidence of catastrophic tool failure, to improve tool life and coatability, and to ensure consistent tool performance.

Bouzakis et al. [1] showed that an increase in the edge radius of coated cemented carbide inserts from 8 µm to 35 µm decreased the maximum mechanical stress in the cutting edge, in a milling application. This was found to translate favourably into a delayed onset of coating fracture and a four-fold enhancement in tool life. Similar results were obtained by Rech et al. [2] in dry gear hobbing when using coated high speed steel (HSS) tools. Their work further indicated the existence of an optimum edge radius value that corresponds to the maximum tool life. Klocke and Kratz [3] demonstrated that it is feasible to forestall catastrophic failure of polycrystalline cubic boron nitride tools in hard turning applications, by a systematic variation of the edge geometry along the cutting edge profile. Karpuschewski et al. [4] recently reported that honing the cutting edges of HSS twist drills diminished the occurrence of edge chipping by a factor of three, while enhancing drill life by about 100%.

As attested to above, the significance of edge preparation in the performance of cutting tools in reference to diverse tool materials and machining processes cannot indeed be overemphasized. Accordingly, several edge preparation technologies have been developed [5], the most common of which are brush honing and micro-blasting. Brush honing involves material removal using a tool with synthetic bristles impregnated with abrasive grits, wherein the hone geometry is controlled essentially by the level of engagement of the cutting edge with the brush and the processing time. Micro-blasting entails the erosive effect of fine abrasive particles entrained in a pressurized air stream; alternatively, a viscous or granular media may be involved.

An issue with the aforementioned processes is the significant inherent variability [6] in the geometry of the generated edge, not just between cutting edges but also along the same edge. Further to problems with process control, mechanical edge preparation methods are somewhat limited in terms of their application to tool materials such as polycrystalline diamond on account of their extreme hardness. In this context, the research detailed in this paper presents the proof-of-principle of the novel application of electrical spark discharges for precision, non-contact edge preparation of cutting tools.

2. Process concept

It is a well-known issue in sink electrical discharge machining (EDM) that machining of intricate geometries with sharp features requires the application of several electrodes to successively confer the required geometry, due to deterioration of the tool shape, which generally manifests itself as rounding of sharp edges [7]. Be as it may a problem in EDM, this phenomenon can be exploited to generate controlled edge radii on cutting tools, by sinking the sharp cutting edge into an appropriate counterface material. This concept represents an innovative perspective that expands the application envelope and capability of EDM in the area of cutting tool manufacture. In light of the variability inherent to conventional edge finishing technologies, the general high level of precision associated with EDM processes would be advantageous in terms of generating consistent hone geometry, as demonstrated later. Furthermore, as the mechanism of material removal is melting and vaporization as opposed to abrasion, material removal is not influenced or limited by the hardness of the tool material; it just needs to possess the requisite electrical conductivity.

Systematic research into tool shape evolution in EDM was conducted by Crookall and Fereday [8] who invoked the concept of relative duty to elucidate the phenomenon of rapid shape degeneration of sharp corners. This notion considers that the macroscopic relative erosion rate observed between the tool and the work holds also at the micro-scale, across the spark gap. This implies that regions with a curvature in an electrode would entail a greater rate of recession, in comparison to linear segments. In addition to the geometric effect above, the accumulation of heat in the edge would further accentuate the effect of relative duty, especially in micro-EDM applications, when employing materials with poor thermal properties [9].

Fig. 1 shows the schematic of an edge that was sharp (with a radius approaching zero) at the outset being sunk into an initially flat (referring to an infinite radius) counterface. This geometry corresponds to an extreme relative duty, and the sharp edge would hence degenerate virtually instantaneously; thereafter, the increase in curvature would progress at a rate consistent with the disparity in the relative duty between the electrodes. For unit thickness into the plane of Fig. 1, for the included angle β = 90°, the volume of material V_t that has to be removed from the tool in order to generate a hone of radius r_β can be calculated as:

$$V_t = r_\beta^2 (1 - \frac{\pi}{4}) \quad (1)$$

For a given material removal rate, a higher included angle corresponds to a lower machining time to attain the same edge radius [8]. Neglecting the roughness of the surface, for nominal in-feed of the tool into the counterface, the volume V_c of material that is to be removed from the counterface to generate a honed edge of radius r_β is determined by the working gap width s, such that a radius ($r_\beta + s$) is generated on the counterface, and is given by:

$$V_c = (r_\beta + s)^2 (\frac{\pi}{4} - \frac{1}{2}) \quad (2)$$

When using sink EDM to generate edge hones, there are several possibilities in terms of kinematic motions between the tool edge and the counterface. For instance, asymmetric hones (e.g. waterfall hones) can be generated by tilting the edge relative to the feed axis in the plane of Fig. 1. The edge can be inclined also along the cutting edge (into the plane of Fig. 1) to induce a variation in edge radius, appropriate for machining applications wherein the uncut chip thickness varies along the cutting edge.

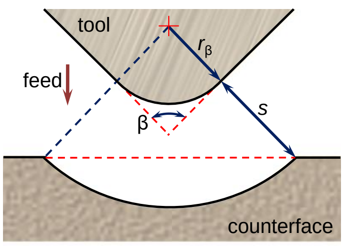

Fig. 1. Schematic representation of electro erosion edge honing.

3. Experimental

As a first experiment, the kinematic employed in the present work refers to symmetric sinking of the tool edge on to a flat counterface as shown in Fig. 1. The objectives of the experimental work were to: (i) prove the concept of using electrical spark discharges for honing the edges of cutting inserts, (ii) investigate the shape evolution of the cutting edge geometry with reference to counterface material, machining time and pulse parameters, (iii) assess the effectiveness of edge hones generated using spark discharges by conducting tool life tests, and (iv) quantify the variability in edge geometry both along and between edges.

An important component of this work was the measurement of the cutting edge radius, which was accomplished using a confocal microscope. Cubic non-uniform rational B-spline (NURBS) surface models were fit to the point cloud data obtained using the confocal microscope, with 30x30 control points, chord length parameterization and knot vector. This measurement technique was verified by a tactile form tracer and a white light interferometer. The uncertainty in edge radius measurement was estimated to be less than 1 µm.

Experiments primarily involved finish-ground, uncoated AISI T-15 grade HSS inserts of specification SNEA 320 (included angle β = 90°, edge length 10 mm) with sharp edges; limited results relate to C-2 grade uncoated cemented carbide. Edges were electro-erosion honed using a solid state power supply, in an oil-based dielectric fluid, with no external flushing, at constant servo sensitivity. The baseline process parameters were: positive polarity on aluminum counterface, open circuit voltage U_o = 100 V, working voltage U = 80 V, on-time t_i = 0.6 µs, duty factor τ = 0.5, peak current i_e = 1.8 A, and machining time = 80 s, unless stated otherwise. These parameters were selected on the basis of extensive preliminary experiments, for the electro-erosion honing cycle time to be comparable to conventional processes, when employing conservative pulse parameters that relate to the micro-EDM regime, in the interest of maintaining the integrity of the functional surface generated.

4. Results and discussion

Figs. 2a and 2b show NURBS representations of HSS cutting edges along with aluminum and copper counterfaces, respectively, with the gap between them expanded for clarity. The corresponding wear ratios ν (ratio of the volumetric material removal from the cutting edge to that from the counterface) were calculated to be 0.5 and 7.5. While the edge prepared using the aluminium counterface is rounded (machining time 120 s, edge radius 40 µm), use of a copper counterface results in an edge that entails a flat land. The figure highlights the critical influence of the counterface material and hence the wear ratio on the meso-geometry generated on the cutting edge, and the flexibility the process offers in terms of generating both hones and chamfers.

When a sharp edge is sunk into a counterface, for uniform debris distribution in gap space, successive spark discharges can be considered to occur at locations that relate to the closest distance between them, which results in the shifting of the discharge location in the working gap. For a tool and counterface shown in Fig. 1, the generation of the rounded edge geometry can be visualised as the outcome of the intrinsic radial movement of the discharge location in the annular working gap of width s, about

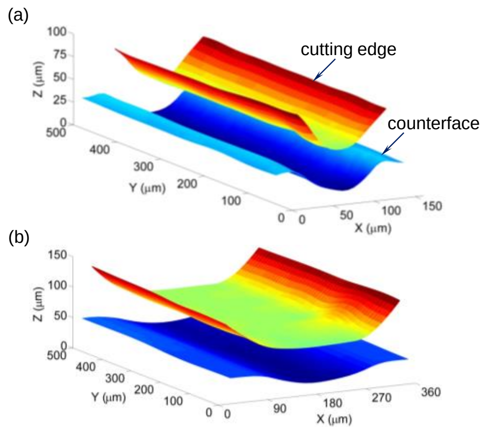

Fig. 2. Effect of counterface material on edge geometry: (a) aluminum, (b) copper.

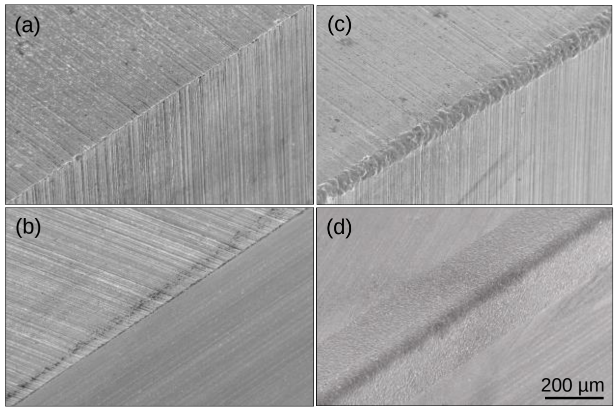

Fig. 4. Micrographs of: (a) HSS and (b) cemented carbide ground (sharp) edges; (c) and (d) are the corresponding electro-erosion honed edges.

the center of the arc generated in the tool. It is interesting to note that such radial excursion of the discharge location obviates the need for any elaborate relative kinematics between the tool and the counterface to generate the rounded edge.

To realise such a radial movement of the discharge location, it is essential that a minimum volume of material, as determined by the instantaneous edge radius r_β and gap width s is removed from the counterface, which does correspond to a threshold wear ratio. For limited in-feed of the cutting edge into the counterface as portrayed in Fig. 1, an approximate limiting wear ratio can be calculated by way of eqns. 1 and 2. For wear ratios higher than the limiting value, a chamfer rather than a hone will be generated. For parameters corresponding to Fig. 2a (r_β = 40 μm, s = 15 μm) the limiting wear ratio as given by eqns. 1 and 2 works out to ~0.4, which explains the generation of the chamfer rather than a hone when a copper counterface (wear ratio of 7.5) is used (Fig. 2b). Lower wear ratios, on the other hand, lead to significant in-feed of the cutting edge into the counterface.

In addition to the simple model above, a numerical geometric simulation [10] was accomplished in the present work to understand shape generation in the spark erosion edge preparation process, by systematically varying the wear ratio over a wide range. Typical simulated tool edge profiles for different wear ratios are shown in Fig. 3, for a gap width of 15 μm. The shape of the simulated profiles clearly indicates the progressive graduation of the edge shape from a hone to a chamfer, with an increase in the wear ratio. The profiles shown for wear ratios of 0.5 and 7.5 can further be seen to concur qualitatively with the shape of the profiles shown in Figs. 2a and 2b, respectively, which refer to these ratios experimentally. Results presented henceforth refer to the application of an aluminum counterface.

Figs. 4a and 4c are scanning electron micrographs of unprepared (ground) and electro-erosion honed HSS cutting edges. A topography that is characteristic of EDM surfaces can be seen along the cutting edge in Fig. 4c. Figs. 4b and 4d refer to cemented carbide edges; the honed surface on the carbide edge can be seen to be smoother, in comparison to the corresponding HSS edge. Micro-chipping along the cutting edge was present in both unprepared HSS and carbide inserts. It can be observed that while the hone is localized along the edge in the case of the HSS insert (Fig. 4c), the EDM surface extends appreciably further into the rake and clearance faces in the case of the carbide insert (Fig. 4d). This is due to the very low wear ratio (~0.01) pertaining, which results in substantial in-feed of the carbide edge into the aluminum counterface. It may be noted that the extraneous material removal on the lateral faces of the tool due to the incursion of the spark discharges away from the tool edge can be observed also on the simulated edge profiles in Fig. 3, for the relatively low wear ratio of 0.1.

Fig. 5 shows primary traces of typical HSS cutting edges obtained using a profilometer with a stylus of tip radius 5 μm, at various machining times to indicate the evolution of the edge geometry. Micro-chipping seen on the unprepared edge sustained from the preceding grinding operation essentially limits the minimum edge radius that can be generated at this section of the edge. The geometry of honed edges was found to be best approximated as circular arcs [8], the radii of which were estimated by circular regression. The figure shows the fit circle for one of the profiles; the maximum absolute radial deviation of the actual shape with respect to the corresponding fit circles for the profiles shown was less than 5% of the edge radius. It is evident from the figure that the rate of increase in the edge radius diminishes with time, which is consistent with the progressive reduction in relative duty. It is instructive to note that the cycle times for electro-erosion honing are comparable to conventional edge preparation processes, and that the relatively low material removal rate of sink EDM is largely inconsequential in this process, as the volume of material that is to be removed from the ground edge to generate the hone is minimal.

The mechanisms of material removal and energy transfer in micro-EDM (pulse energy <100 μJ) are currently not well understood [9]. As indicated before, the pulse energy in the present work (~85 μJ) was determined in consideration of the removal rate and the surface integrity. Experiments with tool positive polarity related to a higher rate of hone radius generation, in line with the favorable energy distribution at the

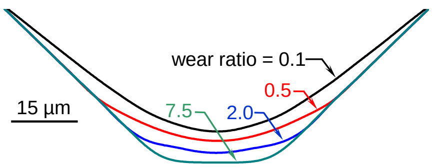

Fig. 3. Simulated effect of wear ratio on edge geometry.

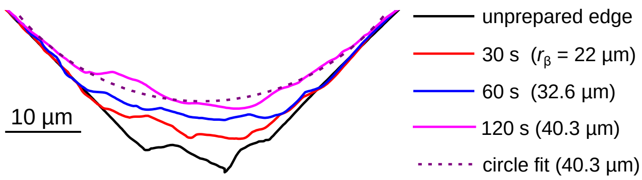

Fig. 5. Profilometer traces of HSS edges showing their evolution.

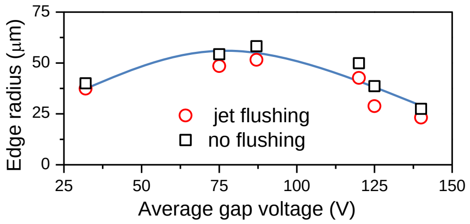

Fig. 6. Effect of gap voltage and flushing on edge radius.

anode; however, this resulted in significant edge hone variability along the cutting edge, and hence a tool negative polarity was adopted. The effect of working voltage and flushing were investigated (Fig. 6) at an open circuit voltage of 150 V. The optimum working voltage is a consequence of the reduction in the actual pulse energy due to an increase in the ignition time delay associated with larger gap widths at higher gap voltages. External jet flushing somewhat reduced the radius values conceivably due to induced discharge instability.

The efficacy of electro-erosion honed HSS edges was evaluated in terms of tool life when cutting annealed AISI 1045 steel, which was assessed using a variable speed test [11] in a facing operation (0.15 mm feed, 0.5 mm depth of cut), for a tool life criterion of 300 µm maximum flank wear. Fig. 7 shows the Taylor's tool life plots, which exemplifies a manifold enhancement in tool life, which is on an order similar to that realized elsewhere [1-4], through conventional edge honing processes. The improvement in tool life can be attributed to: (i) a reduction in the maximum tool temperature due to improved heat dissipation associated with the larger contact area of honed edges [12], and (ii) an offset in the negative influence of grinding-induced tool micro-chipping (Fig. 5). The tool life results affirm the observation in [13] that finish-EDM processes can be engaged to generate critical tooling surfaces with no functional detriment. It is intriguing that the rather low volume of material removal involved in electro-erosion honing allows for the use of conservative spark energy levels, with no adverse affect on either the cycle time or the metallurgical integrity of the edge.

As alluded to previously, an issue with conventional edge honing technologies is the variability in the edge geometry. Schimmel et al. [6] characterized the edge geometry of commercially procured inserts and reported that the measured radii deviated from the specified nominal value by as much as 43%, along the same cutting edge as well as between inserts. In fact, such significant variability is indicative of the reason that most manufacturers specify hones in rather wide ranges of radius values. In order to characterize the variability in electro-erosion honing, 140 edge radius measurements were taken along a single HSS edge over a length of 10 mm, which indicated the mean and standard deviation to be 32.1 µm and just 1.6 µm, respectively. It should be noted that the parallelism of the tool edge with respect to the counterface (into the plane of Fig. 1) is critical in terms of the edge radius repeatability along the edge. The variability between edges was also assessed, the results of which are presented in Fig. 8 as a standard Box plot (box and whisker refer to the 25/75 and 1/99 percentiles, respectively), which substantiates the relatively good repeatability of the electro-erosion edge honing

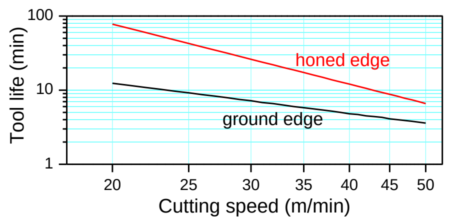

Fig. 7. Effect of edge preparation on tool life.

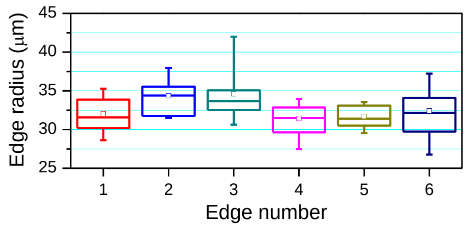

Fig. 8. Box plot showing edge radius variability between edges.

process, which is to be expected of controlled EDM processes.

5. Conclusions

The proof-of-concept of the novel process of using electrical spark discharges for the edge preparation of cutting tools in generating both hones as well as chamfers has been established. The counterface material (and hence the wear ratio) has been identified to be critical in terms of the edge geometry. Edge hones generated using electrical discharges have been shown to correspond to a manifold increase in tool life, in comparison to ground edges. The variability in the geometry of edges generated has been found to be minimal, when compared to values reported for conventionally prepared edges, for both along a single cutting edge as well as between edges.

Further work will focus on electro-erosion honing of composite tool materials, particularly polycrystalline diamond that has an electrically non-conducting phase.

Acknowledgements

This work was funded by the AUTO21 Canadian Network Centers of Excellence and the C4 Consortium of Ontario.

References

1. K.D. Bouzakis et al., 2002, Effect of the cutting edge radius and its manufacturing procedure on the milling performance of PVD coated cemented carbide inserts, *CIRP Annals* 51/1:61-64.
2. J. Rech et al., 2005, Influence of cutting edge radius on the wear resistance of PM-HSS milling inserts, *Wear* 259:1168-1176.
3. F. Klocke, H. Kratz, 2005, Advanced tool edge geometry for high precision hard turning, *CIRP Annals* 54/1:47-50.
4. B. Karpuschewski, O. Byelyayev, V.S. Maiboroda, 2009, Magneto-abrasive machining for the mechanical preparation of high-speed steel twist drills, *CIRP Annals* 58/1:295-298.
5. L.K. Gillespie, *Deburring and Edge Finishing Handbook*, Society of Manufacturing Engineers, Dearborn (1999).
6. R.J. Schimmel, J. Manjunathiah, W.J. Endres, 2000, Edge radius variability and force measurement considerations, *Journal of Manufacturing Science and Engineering* 122:590-593.
7. N. Mohri, M. Suzuki, M. Furuya, N. Saito, 1995, Electrode wear process in electrical discharge machining, *CIRP Annals* 44/1:165-168.
8. J.R. Crookall, R.J. Fereday, 1973, An experimental determination of the degeneration of tool-electrode shape in electro-discharge machining, *Microtecnic* 17:197-200.
9. Y. Y. Tsai, T. Masuzawa, 2004, An index to evaluate the wear resistance of the electrode in micro-EDM, *Journal of Materials Processing Technology* 149:304-309.
10. M. Kunieda, W. Kowaguchi, T. Takita, 1999, Reverse simulation of die-sinking EDM, *CIRP Annals* 48/1:115-118.
11. E.J.A. Armarego, R.H. Brown, *The Machining of Metals*, Prentice Hall, Englewood Cliffs (1969).
12. Y.C. Yen, A. Jain, T. Altan, 2004, A finite element analysis of orthogonal machining using different tool edge geometries, *Journal of Materials Processing Technology* 146:72-81.
13. B. Lauwers, J.P. Kruth, W. Eeraerts, 2005, Wear behavior and tool life of wire EDM-ed and ground carbide punches, *CIRP Annals* 54/1:163-166.