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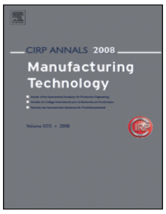

Tool edge honing using shear jamming abrasive media

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Abstract: Nature is replete with fascinating landscapes sculpted through interactions with moving fluids. Drawing inspiration from such, this research investigated intriguing mechanisms underlying the novel application of abrasive non-Newtonian media for rounding sharp edges of cutting tools. Through appropriate deformation, these media may be forced to correspond to rapid and reversible variations in viscosity that span several orders of magnitude, which render them particularly suited to this application. The innovative process is demonstrated to be uniquely capable of honing tools of a complex macrogeometry, generating edges that are symmetric/asymmetric and those that comprise a gradient in microgeometry along the edge length.

Keywords: Cutting tool, Flow, Honing

1. Introduction

The microgeometry of a cutting edge exerts a significant influence on virtually every machining response. A rather belated appreciation of this has recently intensified research on edge preparation, with an emphasis on edges tailored to specific machining applications. A comprehensive review of abrasive processes available for tool edge honing can be found in [1]. Generation of honed edges in such processes is similar to the formation of pebbles with rounded edges, which are shaped naturally over time through erosion and/or abrasion.

Micro-blasting entails erosion of edges by abrasives entrained in a carrier fluid accelerated through a nozzle. Given the numerous parameters of influence, the process is flexible but somewhat complex to control. Brushing involves two-body abrasion of the edge by abrasive grits dispersed on filaments in a rotating wheel. The process is fairly simple but is not readily applied to edges of a complex geometry and is prone to variability arising from filament wear. The brush may be replaced with an elastic-bonded polishing wheel for enhanced performance; however, the process kinematics necessitate 5-axis machine tools [2].

In drag finishing, tools are rotated and translated against a bed of free abrasives and filler particles for edge honing through three-body abrasion. The process is capable of generating uniform edges, but it corresponds to a relatively higher processing time and is largely limited to symmetric edges. Cutting edges may be honed also using abrasive slurries. In abrasive flow machining, honing is accomplished through abrasives suspended in a viscous putty that is pressurized locally by constraining its flow path. Ref. [3] reports on a novel honing process wherein abrasives are mixed into a magnetic fluid, and the viscosity of the slurry thereof is controlled by varying the magnetic field strength.

Despite significant advances, there currently is a need for the conception and development of novel edge honing processes, adequately complemented by fundamental research to solidify process understanding. Accordingly, the research presented in this paper focussed on the technology and mechanisms underlying the application of non-Newtonian abrasive media for cutting tool edge honing. The slurry used was a dense aqueous mixture of cornstarch and abrasives. As opposed to magneto-abrasive honing [3] that uses an external energy source to vary the consistency of the slurry, the cornstarch mixture can be transformed from being a free-flowing liquid to a solid-like state in a rapid and reversible manner by just varying the process kinematics.

The novel application of such shear-thickening slurries as it pertains primarily to surface finishing and a very rudimentary proof-of-concept of edge honing have previously been presented in [4]. The shear-thickening effect has been used also in [5] to polish tool insert surfaces. The present research expanded on [4] in terms of the edge honing application, and in particular perused process mechanisms that revealed several rich and counterintuitive physical phenomena, which are presented in this paper. This work also explored the capability of the process in generating asymmetric and gradient-microgeometry edges, and its application to tools with a complex macrogeometry.

2. Experimental

Figure 1 shows the experimental setup. The tool was rotated in place about a vertical axis, in the annular space of a bowl that rotates about a parallel axis and filled with the abrasive slurry to a depth of $\sim$40 mm. The tool and the bowl could be rotated in either direction; the orbital linear speed of the bowl and the rotational speed of tools of various diameters were largely 10 m/min and 3000 rpm, respectively. The tool was located with radial and axial gaps of 2 mm relative to the outer boundary and the floor of the bowl. The slurry comprised 50% cornstarch by weight in water, on to which a mix of Al_2O_3 abrasives of 68 μm and 17 μm in size at corresponding weight % of 2.5 and 15 were added. The effects of these variables and the rationale for the choice of their baseline values above are discussed later in this paper.

The research involved honing of ground high speed steel (HSS) inserts and twist drills, cemented carbide ball-nose inserts, and solid carbide tapered helical end-mills. Process performance was assessed in terms of changes to the microgeometry of edges that were nominally sharp to start with, for a typical cycle time of 5 minutes. Edge geometry was characterized using an optical confocal surface measurement system.

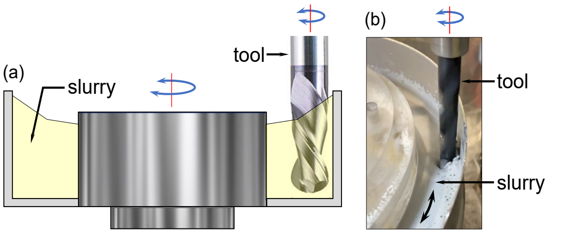

Fig. 1. (a) Schematic and (b) photograph of experimental setup.

3. Results and discussion

3.1 Process mechanisms

Tool edges rotated in-place in a static mixture (Fig. 2a) and those that were subject to an orbital motion alone (red arrows, Fig. 2b) indicated no appreciable changes to the edge microgeometry (Fig. 2d), even for a wide range of speeds and edge orientations. The leading edge was however honed (Fig. 2e) with a pronounced asymmetry ($S_2 > S_1$) under simultaneous orbital and rotational motions in the vicinity (~mm) of a rigid boundary (Fig. 2c).

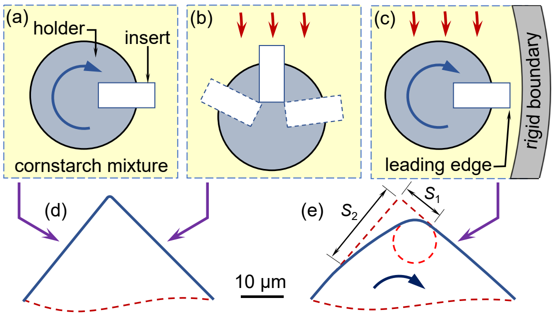

Fig. 2. Role of orbital and rotational motions in edge rounding.

Dense aqueous cornstarch suspensions exhibit non-Newtonian behaviour in that their viscosity changes with shear rate. At sufficiently high particle fractions, the viscosity increases by several orders of magnitude when the shear rate exceeds a threshold, which is called Discontinuous Shear Thickening (DST). Current consensus [6] attributes this to frustrated dilatancy (tendency of granular material to increase in volume under shear), for instance by a rigid boundary as that in Fig. 2c. In this regime, particles breach viscous forces and establish frictional contacts that percolate a granular network of force chains, exerting normal stresses that are proportional to shear stresses. With abrasive grits in the mix, DST in the gap between the edge and the boundary could plausibly have induced the observed modification to the edge microgeometry (Fig. 2c).

To verify the hypothesis above, the progression of the radius r_β of HSS edges corresponding to a single rigid boundary (as in Fig. 2c) was compared against that from parallel dual boundaries, with the tool positioned equidistant to both. Fig. 3 shows the honing performance to be virtually identical, refuting the hypothesis: had DST been the primary mechanism, the double boundary should have corresponded to a considerably better if not twice as good of a performance. Fig. 3 further demonstrates the capability of the process to hone HSS edges of $r_\beta \approx 25$ µm in under 2 minutes, and to generate large ($r_\beta \approx 100$ µm) edge hones.

Further experiments pointed to edge honing being contingent upon appropriate directions of orbital and rotational motions (Fig. 4). Relative to the directions shown in Fig. 4a (same as in Fig. 2c) wherein the leading edge (blue) was honed, reversing the orbital motion resulted in a negligible change to the edge geometry (Fig. 4b). Concurrent reversal of the rotational direction did but restore honing (Fig. 4c), again at the leading edge (red).

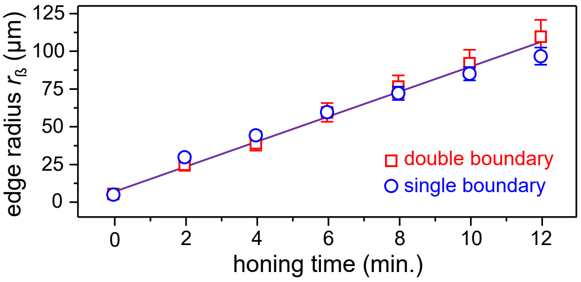

Fig. 3. Performance from single and double boundaries.

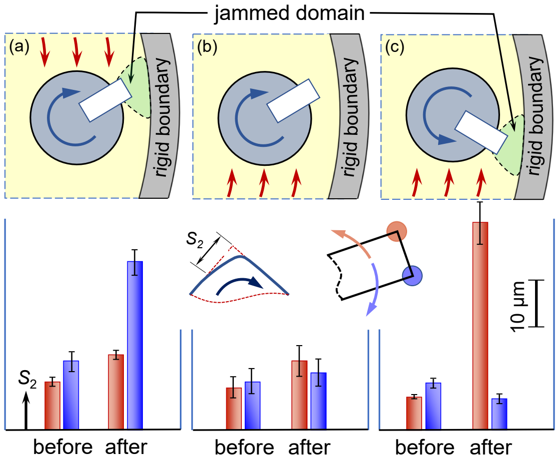

Fig. 4. Effect of process kinematics on edge microgeometry.

This suggests honing to be a consequence of Dynamic Shear Jamming (DSJ), which is a response of the fluid mixture to forcing that transiently transforms it into a solid-like state. Flow fields obtained using ultrasound imaging have recently clarified [7] the mechanisms underlying DSJ. Forcing the mixture, say with an indenter, has been observed to trigger a shear front that propagates at an axial speed ~10 times as high, which reorganizes particles in its wake into a jammed state (Fig. 5a). Within this jammed domain that is supported by the inertia of the fluid around it, frictional contact between particles assembles a force-bearing network, with no significant particle densification.

On further propagation (Fig. 5b), the shear front interacts with the rigid boundary, developing a static region that is driven deeper into the shear jammed state. At this stage, the indenter and the rigid boundary are linked by a solid-like column in between. This can sustain normal stresses (in proportion to the shear counterpart) of several MPa, which is orders of magnitude higher than that possible in DST [6]. On cessation of forcing, the stresses are insufficient to maintain frictional contacts, which reverts the mixture back to its fluid-like state. DSJ has been reported also in simple shear and under extensional loading [7].

Noting that jamming manifests in front of the moving object, the resultant of orbital and rotational motions ahead of the tool in Fig. 4a and 4c is directed towards the rigid boundary, which facilitates its interaction with the jammed domain. Owing to the normal stresses pertaining, this shear jammed domain functions as a solid-like but compliant counterface that supports and indents abrasive grits into the tool edge rotating past and hones it in the process, conceivably through three-body abrasion. The directions of the motions in Fig. 4b on the other hand are not conducive to such an interaction with the boundary, as verified through force measurements in [4]. This model also explains the data in Fig. 3: as the jammed domain can interact with only one boundary for a given process kinematic (Fig. 4), the addition of another boundary would indeed not enhance honing performance.

When the leading edge was honed, the trailing edge underwent just a slight increase (Fig. 4a) or even a decrease (Fig. 4c) in S_2. Considering that S values are prone to variability associated with characterization, an experiment was conducted with a symmetric edge of a fairly high r_β (47 µm) at the trailing edge to

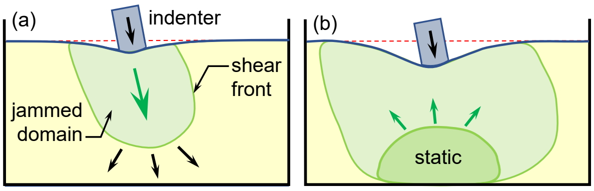

Fig. 5. Mechanism of dynamic jamming; adapted from [7].

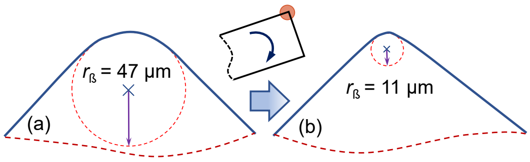

Fig. 6. Sharpening of the trailing edge.

comprehend phenomena that transpire there. The radius r_β was found to decrease significantly to 11 µm (Fig. 6), confirming "sharpening" of the trailing edge.

This is somewhat similar to the shape evolution of spherical erodible clay structures in a stream of water [8]. Seeding indicated the flow to encounter the sphere at the stagnation point S (Fig. 7a) and conform to it until separation at P, downstream of which vortices were formed. Such fluid-structure interaction resulted in the sphere transforming into a quasi-triangular shape (Fig. 7b), with its rear rendered remarkably flat by the wake.

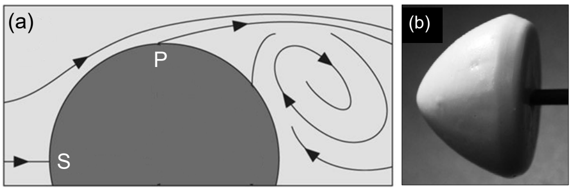

Fig. 7. Erosion in a water stream; reproduced with permission from [8].

Since flow patterns in the opaque cornstarch mixture cannot be visually observed, grinding marks on a rough-ground HSS insert were used as markers. After honing, the leading edge indicated grinding striations to be preserved on both the top and side faces that flank the honed region (between the red broken lines, with a lay pattern normal to the grinding marks, Fig. 8b). The trailing edge on the other hand showed a smooth top face with grinding marks removed entirely, in contrast to the side face where they remained intact (Fig. 8a). This suggests streamlines shown schematically in Fig. 8c: the flow interacts with and hones the leading edge L before separating off this edge; it then reattaches on the top face and translates forward sharpening the rotating trailing edge T. Grinding marks staying put on the side face of the trailing edge points to the absence of any vortices as in Fig. 7, likely due to the jammed domain being very viscous. Overlaying the profiles from Fig. 6 confirms edge sharpening to be due to the removal of the wedge-shaped sliver of material (shown shaded in Fig. 8d) from the trailing edge by the reattached flow.

Abrasive size also exhibited interesting influences on the process. Fig. 9a & 9b show r_β along the edge of an insert for various grit sizes, relative to a sharp edge. An increase in abrasive size generally improved honing performance in alignment with the knowledge that larger grits are more effective in abrasion.

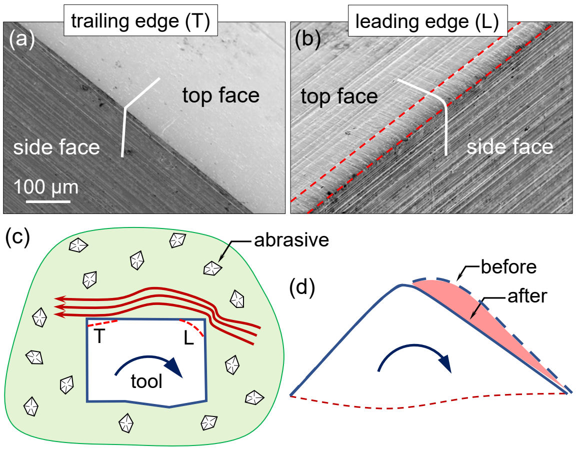

Fig. 8. Mechanism of sharpening of trailing edge.

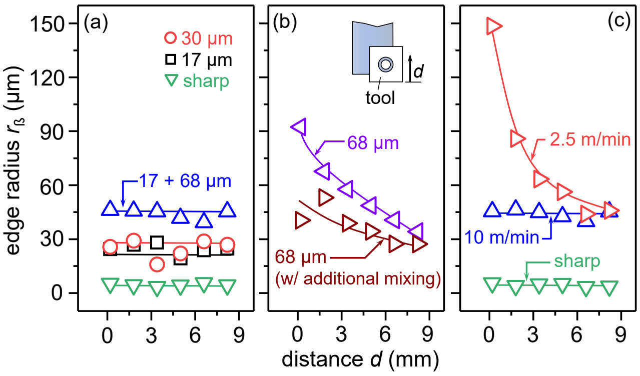

Fig. 9. Effect of grit size (a,b) and orbital speed (c) on distribution of r_β.

Increasing the grit size to 68 µm did but skew the distribution of r_β (Fig. 9b). Supplementary experiments showing r_β to increase linearly with abrasive % suggested this to be due to migration of abrasives towards the bottom. The addition of a mixer in the vicinity of the edge being honed reduced the segregation (Fig. 9b) corroborating this. It is interesting that such segregation is not driven entirely by a difference in density, since it did not occur for the finer abrasives.

Granular mixtures exhibit intriguing vertical segregation under shear and gravity [9]. In some instances, large dense particles migrate upwards in apparent defiance of physics, which is known as the Brazil Nut Effect. This is in part due to smaller particles selectively falling into flow-induced voids that nucleate randomly between shear layers, which ratchets the larger particles upwards. Under other conditions, heavier particles push open their way into lower shear layers, which promotes their migration downwards. Crossover thresholds that inhibit such segregation are complex and are sensitively dependent on the size and mass ratios of the constituents, in addition to their shape, roughness and concentration, and the forcing/boundary conditions [9]. It was therefore expedient to adopt the discovery in [10] that the addition of a ternary species deters segregation mechanisms towards promoting mixing. A combination of 17 µm and 68 µm grits did accordingly render r_β to be relatively uniform (Fig. 9a). Even for such a slurry, effective mixing required the stirring from high enough (10 m/min) of an orbital speed (Fig. 9c).

3.2 Applications

With the insert held radially in the tool holder (Fig. 2c), the honed edge is inherently asymmetric. This could be altered by changing the inclination θ of the insert (analogous to the setting angle [1] in brushing and micro-blasting) in the tool holder (Fig. 10a), which in turn modifies the angle at which the edge is presented to the jammed domain. A symmetric edge could be obtained for $\theta \approx 35°$ (Fig. 10b). A micrograph of such an edge (0.4 µm *Ra* edge roughness, HSS) is shown in Fig. 11a, alongside a ground edge (Fig. 11b) for a perspective. Experiments relating to Fig. 3, 6 and 9 entailed symmetric edges that were honed using such an insert configuration. The orientation of edge asymmetry could be changed by further increasing θ; however, both waterfall- and trumpet-shaped edges may rather be generated by simply flipping the insert in the radial tool holder (Fig. 2c) as appropriate.

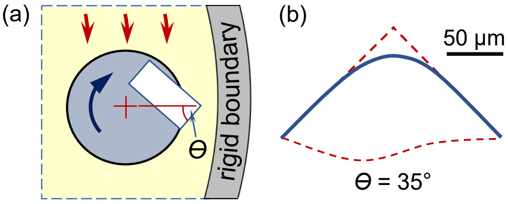

Fig. 10. Generation of a symmetric edge.

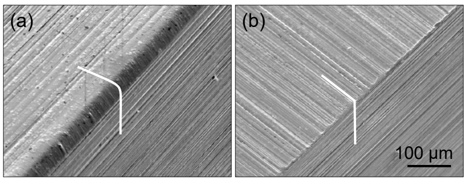

Fig. 11. (a) Symmetrically honed, and (b) sharp edges.

An application of the serendipitous edge sharpening phenomenon (Fig. 8) relates to the refurbishment of solid tools, which is shown with respect to a twist drill as an example (Fig. 12). Owing to the conformance of the viscous abrasive slurry to the geometrically complex flank faces of the drill, worn edges could be sharpened by just rotating the drill in a direction counter to that during drilling. This obviates the need for any manual skill or complex grinding kinematics. Subsequent to sharpening, the edges can further be honed in-place by basically reversing the rotational direction to be the same as that when drilling (Fig. 12).

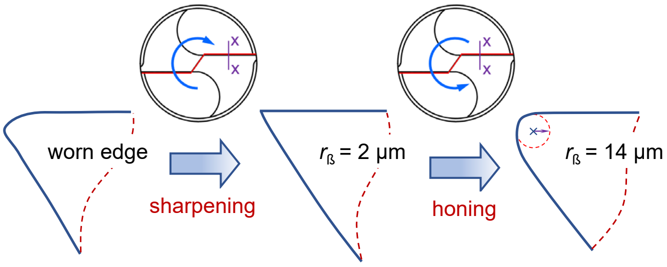

Fig. 12. In-place refurbishment of worn drills.

Edges with a gradient microgeometry along their length are advantageous in accommodating the variation in uncut chip thickness inherent to processes like ball-end milling. Generation of such edges that is otherwise challenging is quite straightforward in this process. Fig. 13 shows a gradation in r_β along the curved edge of a 12 mm diameter cemented carbide ball-nose insert, which was honed by securing it on the corresponding tool holder (–10° axial rake, 0° radial rake). The honed edges were of 0.2 µm *Ra* roughness. Halving the tool speed from 3000 rpm reduced r_β significantly from 14 µm to 8 µm at location 3, while a three-fold increase in the radial gap showed relatively little change. It follows therefore that the gradient in r_β is related to the increase in linear speed along the curved edge for a given rotational speed, which translates into an increase in both the local kinetic energy and sliding length of the abrasives. This corresponds to a higher abrasive wear volume and hence a higher r_β.

Honing of a solid carbide end mill (35° axial rake, 0° radial rake) indicated the peripheral edges (Fig. 14a) to be more rounded relative to edges at the tool end (Fig. 14b). This is due to jamming occurring predominantly at the tool periphery. Enhanced honing of the end cutting edges may be accomplished by inclining the tool against the direction of the orbital motion to promote jamming at the bottom face. The honed edges are further asymmetric with $S_\gamma < S_\alpha$ which implies that it is suitable only for applications wherein tool failure is governed by crater wear [1]. That such an asymmetry did not manifest in Fig. 13 appears to highlight the influence of the axial rake angle (–10° vs. +35°) on edge shape generation. In its current state of development, the orientation of edge asymmetry being tied to the geometry of solid tools (which obviously is determined in view of the machining application at hand rather than edge honing considerations) is a limitation of the process.

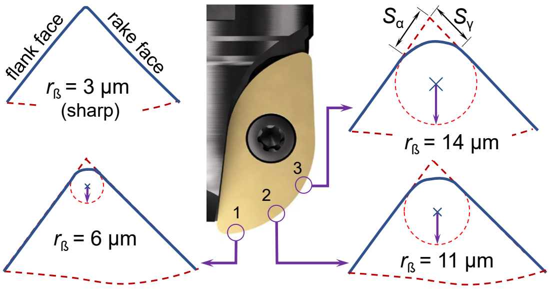

Fig. 13. Variable edge geometry in a ball-nose end mill.

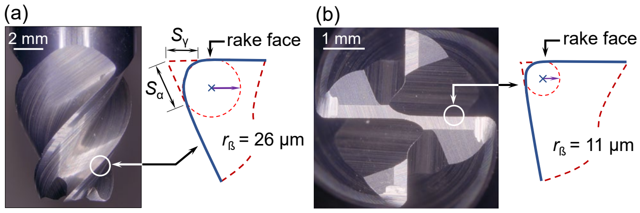

Fig. 14. Edge geometry of tapered helical solid carbide end mill.

4. Conclusions

This paper demonstrated the novel application of non-Newtonian abrasive slurries involving dense aqueous mixtures of cornstarch for generating symmetric/asymmetric and variable microgeometry edges, honing tools of a complex macrogeometry and refurbishment of solid tools. The process mechanism was identified to be dynamic shear jamming that is enhanced by the interaction of the jammed domain with a rigid boundary. The work highlighted the adverse effects of shear-induced vertical segregation of abrasives in the slurry on the uniformity of edge geometry and resolved it by using a combination of two grit sizes. Flow modelling of the process is warranted to further advance process understanding towards controlling the orientation of edge asymmetry irrespective of the geometry of solid tools.

Acknowledgements

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