An Upper-Bound Model of Edge-Radius Effects on Machining Forces

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Introduction
To achieve the edge strength needed to cut harder materials, slightly negative rake angles are used with a honed radius or chamfer applied to the cutting edge. Edge effects become important when the applied geometric feature is sizeable relative to the scale of the cut — the uncut chip thickness (feed). In finish cuts where the feed rate is low, even the “natural” sharpness of a cutting edge becomes sizeable relative to the uncut chip thickness. In these cases, appropriate model-based selection of the edge feature requires a model that explicitly accounts for the edge geometry rather than absorbing its qualitative effect into empirical parameters, as is the case to date in the most commonly used models.

The aim of this work is to develop a machining model that explicitly includes the effects of edge radius without resorting to the highly computational finite element method or the complexities of rigorous slip-line analysis. While it is presumed and/or known that the edge geometry affects surface finish, residual stress, cutting temperature and tool wear, the first step taken here is to model the effects of edge radius on forces. While the model achieved here is not fully predictive, it does provide a means to analyze force data to assess how well the model represents the effects of edge radius on flow stress via the edge radius’ effects on strain and strain rate. Continuing work aims to realize a fully predictive model.

Approach
The model is based on material separating at a stagnation or separation point on the cutting edge, with the material above that point forming the chip and the material below that point forming the machined surface. The geometry of the process is idealized to achieve a deformation zone and equivalent tool each made up of straight boundaries, as shown in Fig. 1.

The equivalent tool geometry is formulated as follows. The edge radius is approximated by two line segments, the vertex of which is the stagnation point — point P. The lower portion of the tool edge radius is replaced by an equivalent chamfer — line segment CP. The rake face and upper portion of the edge radius are replaced by an equivalent rake face — the line segment that connects point P to the point at which the chip leaves the tool. The separation point is located on the edge radius by the separation angle θ, which is ultimately an input. The value of θ is chosen based on various past studies of critical negative rake angle — the extreme negative rake angle at which chip formation ceases. The equivalent rake face is characterized by its equivalent orthogonal rake angle. Supportive of this concept is visual experimental evidence, both in this work and others’ past work, that shows the chip to leave the tool at a direction consistent with a more negative than nominal rake angle.

The deformation zone is defined to be consistent with upper-bound analysis as follows. Plastic deformation initiates at the forward boundary AB, which is a plane of maximum shear stress; hence, AB meets the free surface at 45°. Plastic deformation concludes at the upper boundary AP and at the lower boundary BC. Material above point D, which is at the same level as point C, rises up to the separation point P. Material below point D is plastically deformed down to point B. Lines AB, BP and AP are lines of velocity discontinuity; Fig. 1 shows the velocities in the deformation zone that define the flow and ultimately the strain rates. Boundary AP is representative of the traditional shear plane; hence, it is oriented by the shear angle ψ. Boundary BC is oriented by the angle θ, which then dictates the depth of plastic deformation (point B).

Given the process geometry, the forces are then determined under the premise of equilibrium. That is, that the machining force holds in equilibrium all elements of the system — the workpiece, deformation zone, chip and tool. Forces on a boundary are computed as the product of the normal and shear stresses on the boundary and the length (area) of the boundary. The boundary of choice for computing forces is the lower boundary of the deformation zone (line segments AB and BC). Figure 2 shows the process geometry split at this boundary. The normal pressures P1 and P2, and shear stresses S1 and S2, act equally and opposite on the workpiece and the deformation zone. Summing the resulting forces in the cutting and thrust directions yields the process forces.

To be predictive, however, one needs the values of P and S, as well as all values defining the geometry. The normal pressure can be related to the flow stress S, which can be empirically modeled in terms of strain and strain rate with power-law coefficients obtained from measured forces. A sensitivity analysis shows minimal sensitivity of forces to choices of θ and ψ. However, where this model lacks a “predictive” capability is the lack of a good model for the shear angle ψ. Therefore, the model is used at present only as a means to analyze force data

Results
Force data is analyzed given measured shear angle values by fitting a power-law model for S in terms of strain and strain rate. If the model is well correlated across edge radius, rake angle, and uncut chip thickness, it is considered internally consistent — that is, the model is consistently capturing the internal stress-strain-rate behavior across all geometry.

The model works well across uncut chip thickness and rake angle for sharp tools. However, large data sets across large ranges of edge radius show deficiencies in the model. Continuing work aims to address this issue by modeling the process geometry with curved boundaries that are more consistent with high-magnification images acquired in related work.

Benefits
• The simplicity of the model provides an analytical result that clearly shows effects of geometric parameters.
• However, inconsistencies in exercising the model justify and motivate a more sophisticated model, such as a slip-line field (SLF).