# TOOL LIFE MAXIMIZATION IN CUTTING WITH TWO-EDGED TOOLS : THE IMPORTANCE OF COOLING FACTOR

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**Abstract**

Previous work has shown that a non-dimensional parameter ($\overline{\sigma}_r$), which characterizes the stress intensity in a single-edged cutting tool, is of particular value in the optimum selection of tool geometry. This paper examines the utility of this parameter in the context of two-edged turning tools whose cutting edge inclination angles vary in a wide range. It is shown that, in such conditions, one needs to consider, in addition to $\overline{\sigma}_r$, the influence of the cooling power of the three dimensional wedge. A new measure for the cooling power by virtue of the tool's geometry is developed and tested against experimental tool life data.

## 1. Introduction

Tool life maximization is of great economic significance in the design of any cutting process. This paper addresses the problem of the selection of tool geometry for maximum tool life for a given tool-work material pair in turning with plane faced tools.

Fig. 1 illustrates the geometry of the cutting tip of a plane faced turning tool (using ISO3002/1 nomenclature). The major cutting edge ($e_1$) and the minor cutting edge ($e_2$) together determine the uncut chip section. Usually, the major edge ($e_1$) dominates the cutting process. The plane including the two cutting edges is the rake face (face $A_\gamma$). $A_\alpha$ and $A_\alpha'$ are the clearance faces associated with the major and minor cutting edges respectively. Thus, the tool tip is a three-dimensional wedge formed by three plane faces: $A_\gamma$, $A_\alpha$ and $A_\alpha'$.

Tool life in turning is usually terminated by either fracture or wear in the vicinity of the major cutting edge. Three angles related to the major cutting edge are important in this context. These are the cutting edge inclination ($\lambda_s$), the normal rake angle ($\gamma_n$), and the normal clearance angle ($\alpha_n$). These angles are easily derived once the tool geometry has been fully specified in accordance with a standard such as ISO 3002/1. Sometimes, corner wear or corner fracture may occur in the vicinity of the tool tip. However, such corner failure is usually

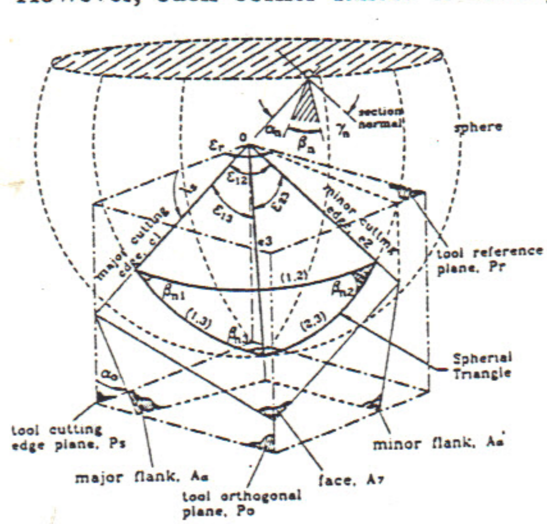


Fig. 1 Geometric Definitions for corner tool

precluded by designing a rounded corner with a small nose radius, $r$. Hence, the present work addresses the problem of optimizing the cutting geometry at the main cutting edge from the point of view of tool life maximization.

Consider the influence of the geometric variables associated with the major cutting edge on the ability of the tool to resist fracture. It is generally known that tools fracture when the maximum tensile stress in the tool reaches a critical magnitude under the cutting load. It is intuitively apparent that the basic tool geometry variables exert their influence on the tool's ability to resist fracture by changing (i) the wedge angle, $\beta_n$ ($= 90^o - \gamma_n - \alpha_n$), and/or (ii) the relative orientation, $O_n$ ($=\alpha_n+\beta_n/2$), of the tool wedge with respect to the cutting speed direction. A tool with a smaller wedge angle ($\beta_n$) and/or with the tool wedge less closely aligned to the cutting force direction (i.e. smaller $O_n$) is likely to experience greater tensile stresses for the same cutting load and, hence, will tend to have lower resistance to fracture during cutting.

Kaldor *et al* [1] have described a simple method for combining the influences of the basic tool geometry variables into a non-dimensional parameter, $\overline{\sigma}_r$, which is a measure of the intensity (tensile) of the radial stress field that arises in the tool when the cutting load is assumed to be *concentrated* at the major cutting edge:

$$\overline{\sigma}_r = cos^2\lambda_s \frac{sin O_n\, sin(\frac{\beta_n}{2})(\frac{\beta_n}{2}+\frac{1}{2}sin\beta_n) - cos O_n\, cos(\frac{\beta_n}{2})(\frac{\beta_n}{2}-\frac{1}{2}sin\beta_n)}{(\frac{\beta_n}{2})^2-(\frac{1}{2}sin\beta_n)^2} \quad (1)$$

Numerous experiments on a wide variety of cutting operations (including turning) have demonstrated that an increase in $\overline{\sigma}_r$ leads to a decrease in tool life, $T$, when the dominant mode of tool life determination is by fracture [1-4]. Thus $\overline{\sigma}_r$ may be taken as a simple measure of the tool's susceptibility to fracture by virtue of its geometry.

Kaldor *et al* [1-4] have noted that, when $\overline{\sigma}_r$ is large, the dominant mechanism of tool life termination is due to fracture. In this range, tool life decreases with increasing $\overline{\sigma}_r$. However, tool life is terminated mainly due to flank wear (at the major edge) when $\overline{\sigma}_r$ is small. In this range, tool life increases as $\overline{\sigma}_r$ is increased. Thus, there exists an optimum value, $(\overline{\sigma}_r)_{opt}$, of $\overline{\sigma}_r$ where the tool's susceptibility towards flank wear is in balance with that towards fracture, and this optimum value characterizes the condition for maximum tool life.

Kaldor *et al* have noted that this $(\overline{\sigma}_r)_{opt}$ depends mainly on the tool/work material pair and is relatively insensitive to variations in cutting conditions [1-4]. More recently, Kaldor and Venuvinod examined over 80 published sources listing machinability data and relevant experimental results and succeeded in developing a quantitative expression relating $(\overline{\sigma}_r)_{opt}$ to tool and work material properties [5]. However, three issues concerning the significance and applicability of eq. 1 have remained unresolved.

Firstly, recall that $\overline{\sigma}_r$ is a parameter characterizing the intensity of the radial stress field in the body of the tool when the cutting force is assumed to be concentrated right at the major cutting edge. Thus, eq. 1 relies on the principle that one need not be particularly concerned with the distribution pattern of a load if the location at which the stresses are desired to be estimated is sufficiently far removed from the location of the load (St Venant Principle). Such a simplified model may be adequate as far as the tool's susceptibility towards fracture in the bulk of the tool, i.e. *away from* the tool work contact zone over which the cutting load is actually distributed, is concerned. However, Kaldor *et al* [1-5] did not clarify why $\overline{\sigma}_r$ has such a noticeable influence on tool life when the latter is predominantly determined by micro fracture or flank wear right at the cutting edge (which is *within* the loading zone).

Secondly, note that eq. 1 states that $\overline{\sigma}_r$ is proportional to $cos^2\lambda_s$ which implies that tool life as determined by a flank wear criterion should (i) significantly decrease with increasing absolute magnitude of $\lambda_s$ , and (ii) be insensitive to the fact whether $\lambda_s$ is positive or negative. However, the work of Kaldor *et al* [1-5] was essentially confined to cutting with small values of $\lambda_s$ (hence, the influence of the $cos\lambda_s$ term was too small to be detected). These observations have not so far been validated when $\lambda_s$ is varied across a wide range.

Thirdly, note that $\overline{\sigma}_r$ characterizes the radial stress field in the tool and that the wedge angle, $\beta_n$, is a parameter determining $\overline{\sigma}_r$. Thus, assuming that tool life is directly influenced by the stress intensity in the tool body, Kaldor *et al* [1-5] have been able to capture the relationship between tool life and $\beta_n$. However, it is intuitively apparent that the wedge angle, $\beta_n$, also influences the ability of the tool to dissipate the heat generated during the cutting process. Therefore there is a need to examine whether $\overline{\sigma}_r$ should be complemented by some measure of the heat dissipation ability (cooling power) of the tool wedge, $\beta_n$ , while characterizing tool geometry in the context of its influence on tool life. Further, note that eq. 1 defining $\overline{\sigma}_r$ refers to is a single-edged tool and therefore has a two dimensional wedge. However, usually, a turning tool has two participating cutting edges and, hence, has a three dimensional wedge (see Fig.1). It is therefore particularly useful to develop a measure for the cooling power of a three dimensional wedge and study its influence on tool life while maintaining $\overline{\sigma}_r$ at an appropriately constant magnitude.

The present paper reports on some of the work done by the authors with a view to clarifying or resolving the three issues described above.

## 2. The relationship between tool life as determined by flank wear and $\overline{\sigma}_r$

Adopting well known principles of adhesive wear, Venuvinod *et al* [6] have developed a model for tool life determined from a flank wear criterion in orthogonal cutting with single edged tools. This model has shown that tool life, *T*, is related to the tool's rake and clearance angles ($\gamma_n$ and $\alpha_n$ respectively) as follows:

$$T \propto 1/\{(cot\alpha_n - tan\gamma_n)(1-m^*\gamma_n)^{15.9}\} \qquad (2)$$

where m* = 0.003 if $\gamma_n \leq 0$ and 0.0055 if $\gamma_n >$ 0, and all angles are expressed in degrees.

Eq. 2 has been shown to correlate well with experimental tool life data obtained while cutting mild steel tubes with single-edged HSS tools within the practical range of tool geometry ($\gamma_n$ = -15° to 15° and $\alpha_n$ = 2° to 20°) [6].

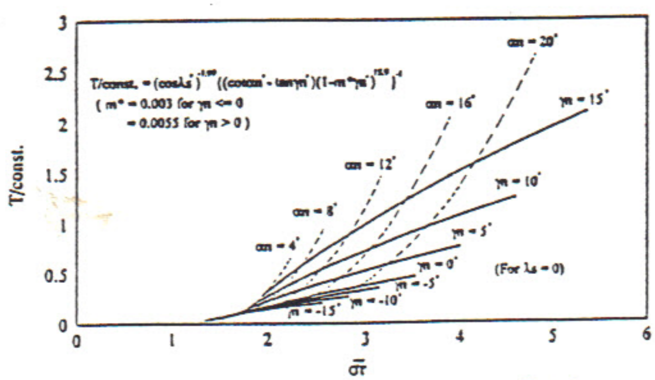


Fig.2 Correlation between T/const. and $\overline{\sigma}_r$ [5]

Fig. 2 shows the relationship between $\overline{\sigma}_r$ as calculated from eq. 1 and the flank wear based tool life estimate given by eq. 2. It can be seen that both $\overline{\sigma}_r$ and the wear based tool life increase monotonously with increasing $\gamma_n$ and $\alpha_n$. While this observation does not clarify the exact mechanisms through which $\overline{\sigma}_r$ influences flank wear, it does provide a basis for us to accept that a larger magnitude of $\overline{\sigma}_r$ should lead to a larger tool life provided that the latter is determined from a flank wear criterion and there is no significant tendency towards tool fracture.

Subsequently, in [7], Venuvinod *et al* extended their orthogonal cutting model described in [6] to oblique cutting with single-edged tools. In particular they derived and experimentally verified (while machining mild steel with HSS tools) the following expression relating tool life, $T$, based on a flank wear criterion to $\lambda_s$ :

$$T \propto 1/\,(\cos\lambda_s)^{3.99} \qquad (3)$$

Note that eq. 3 implies that tool life increases with increasing $\lambda_s$ whereas eq. 1 implies that $\overline{\sigma}_r$ decreases with increasing $\lambda_s$. Thus, it appears that $\overline{\sigma}_r$, as calculated from eq. 1, does not capture the essence of the influence of $\lambda_s$ on tool life.

Further, note that both eq. 1 and eq. 2 had resulted from modeling cutting with single edge tools, i.e. tools with two-dimensional cutting wedges, whereas most turning tools have three dimensional cutting wedges. The next section describes the experimental investigations carried out by the present authors with a view to studying the influence of varying $\lambda_s$ across a wide range while cutting with two-edged tools.

### 3. Experiments with two-edged tools

Turning experiments were conducted on a 10 hp Colchester lathe using bar stock of 200mm diameter consisting of an equivalent of AISI 1050 with hardness 190 HB. HSS tools of 19mm square section were ground to different $\lambda_s$ values in the range -45° to 45°. All tools had a geometrical specification that yielded a $\overline{\sigma}_r$ equal to 2.1 since, according to Kaldor *et al*, this magnitude of $\overline{\sigma}_r$ is expected to result in a cutting state where tool life termination would be dominated by flank wear (note that according to Kaldor *et al*, $(\overline{\sigma}_r)_{opt}$ is equal to 2.5 for machining mild steel with HSS tools [6]). The orthogonal clearance angle at the major cutting edge, $\alpha_o$, was maintained at 8° so that the effect of varying clearance angle is eliminated. Subject to these constraints, the magnitude of $\gamma_n$ was calculated from eq. 1. All tools had a secondary cutting edge angle, $\kappa'_r$, equal to 15° and nose radius, $r$, equal to 1mm. All cutting tests were performed using the following cutting conditions: cutting speed = 60m/min, feed = 0.12mm/ rev, depth of cut = 1.5mm. No cutting fluid was used. The criterion of flank wear land, Vb, reaching 0.1mm was used as the flank wear criterion determining the termination of tool life.

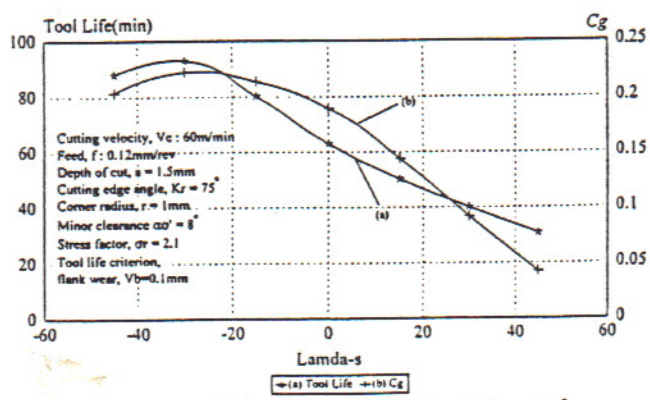


Fig. 3 Variation of Tool Life, *T*, and *Cg* with $\lambda s$

Curve *(a)* in Fig. 3 shows the observed influence of $\lambda_s$ on tool life. Since $\overline{\sigma}_r$ was maintained constant throughout the test range of $\lambda_s$, the observed variation in tool life in the figure can be directly attributed to variation in $\lambda_s$. It is seen that, in the range $\lambda_s \geq -30°$, tool life increases monotonically as $\lambda_s$ is decreased while, in the range $\lambda_s < -30^o$, tool life decreases slightly with decreasing $\lambda_s$. Thus, contrary to the prediction from eq. 3, which relates to single edge cutting (i.e. to tools with two dimensional cutting wedges), tool life is found to be substantially sensitive to the sign of $\lambda_s$ when tools with three dimensional wedges are used. An explanation for these observations is provided in the next section where, in particular, it is hypothesized that these arise due to the influence of $\lambda_s$ on the ability of the tool to dissipate the heat generated in cutting.

## 4. Geometric Cooling Factor, $C_g$

When we consider tools with a major and a minor cutting edge, it is apparent that a tool with a large negative magnitude of $\lambda_s$ is more solidly built in comparison to one with a large positive $\lambda_s$. Hence the cooling power (i.e. heat dissipation ability by virtue of the tool's geometry) of a tool with negative a $\lambda_s$ should be larger than that for a tool with a positive $\lambda_s$.

The cooling power of a two-edged tool may be characterized by viewing the three dimensional wedge formed by faces $A_\gamma$, $A_\alpha$ and $A_\alpha'$ (see Fig. 1) as a solid segment of a sphere of radius $R$ formed with the tool corner as its center. Consider now the nature of conduction heat transfer through the solid segment when heat is generated at a point located at the sphere's center (i.e. at the tool tip) and faces $A_\gamma$, $A_\alpha$ and $A_\alpha'$ are assumed to be insulated. Note that, in the present work, we are not interested in the actual heat flux and temperature fields associated with a specific cutting condition. Clearly, these fields will depend on the nature of and heat flux distributions over the heat generation regions which, in turn, will depend on the prevailing cutting conditions. Neither are we interested in the influence of tool material properties. We merely seek a measure of the tool wedge's ability to carry cutting heat away from the wedge corner by virtue of the wedge's geometry alone, i.e. irrespective of the cutting conditions, heat source distributions, tool material properties, etc.

Now, note that cutting heat is invariably generated in a zone located in the close vicinity of the tool corner whereas, usually, the tool body extends well beyond the cutting zone. Hence, following St Venant Principle again, we may assume that cutting heat is concentrated at the tool tip. In such a situation, since we assume that the other faces are insulated, the cutting heat is dissipated only through the surface patch defined by the spherical triangle subtended by the three-faced tool wedge on the surface of the sphere. Larger the area, $A_{sph}$, of this spherical triangle, larger will be the cooling power of the tool wedge. Now, note that the maximum possible extent of the solid wedge corresponding to the tool body is a hemisphere (we are only interested here in geometric implications; hence we ignore the fact that such a hemispherical segment cannot actually cut). Hence, we may divide $A_{sph}$ by the surface area $(2\pi R^2)$ of the hemisphere so as to yield a non-dimensional measure of the cooling power, $C_g$, of the tool (body). Since $C_g$ characterizes only the influence of the tool's geometry on its cooling power, we shall name it as the *Geometric* Cooling Factor. Now, applying well known principles of Spherical Trigonometry to the geometry of the tool wedge as illustrated in Figure 1, it can be shown that

$$C_g = A_{sph}/(2\pi R^2) = (\beta_{n1}+\beta_{n2}+\beta_{n3} - \pi)/(2\pi) \quad (4)$$

where all angles are expressed in radians. Note that angles $\beta_{n1}$, $\beta_{n2}$, and $\beta_{n3}$ (see Fig. 1) are the wedge angles at edges $e_1$, $e_2$ and $e_3$ respectively. These are easily calculated once the tool geometry has been completely specified (e.g. using ISO 3002/1 specification).

Curve *(b)* in Fig. 3 shows the variation of $C_g$ with $\lambda_s$ as calculated for the tools used in the experiments described in section 3. Note that the nature of curve *(b)* is remarkably similar to that of curve *(a)* which represents the variation of tool life (based on a flank wear criterion) with $\lambda_s$ while maintaining a constant magnitude of $\overline{\sigma}_r$. These results confirm the hypothesis that the variation in tool life with $\lambda_s$, as observed while maintaining a constant $\overline{\sigma}_r$, arises mainly due to the influence of $\lambda_s$ on the ability of the tool body to dissipate cutting heat.

## 5. Conclusion

It is only in the case of orthogonal cutting with single-edged tools that the non-dimensional stress function, $\overline{\sigma}_r$ described by eq. 1 correlates well with tool life predictions obtained by assuming that flank wear occurs mainly due to adhesion mechanisms. This correlation provides a partial explanation to the observation of previous researchers [1-5] that flank wear based tool life increases with increasing $\overline{\sigma}_r$. However, this correlation turns negative in oblique cutting with large magnitudes of $\lambda_s$ (even if the tool is single-edged).

New experimental results have revealed substantial differences between the behaviors of tools with two-dimensional and three-dimensional wedges when $\lambda_s$ is varied in a wide range. The main reason for this is that, unlike in the case of cutting with a two-dimensional wedge, $\lambda_s$ has a significant effect on the cooling power of the tool when its wedge is three-dimensional. As a result, tools with negative $\lambda_s$ yield larger tool lives than those with positive $\lambda_s$.

The geometric cooling factor, $C_g$, as calculated by eq. 4 provides a simple measure of the cooling power of a three-dimensional wedge by virtue of its geometry. The variation of $C_g$ with $\lambda_s$ while maintaining a constant $\overline{\sigma}_r$ is found to be substantially similar to the variation of tool life with $\lambda_s$ under the same cutting conditions. It is concluded therefore that it is necessary to consider the geometric cooling factor ($C_g$) *in addition* to the stress intensity function ($\overline{\sigma}_r$) while selecting the tool geometry of two-edged tools with a view to maximizing tool life.

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