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Optimisation of Tool Setting in Machining with Type II Rotary Tools

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The self propelled rotary tool is a powerful modern tool. Out of its applications, machining of cast iron has been noteworthy. Earlier literature on type I tools shows that tool design for this type is very critical. This has also been confirmed with type II tools. To avoid excessive and lengthy experimentation, a new semi-experimental procedure for efficent optimisation of the tool setting has been devised. A set of iso-rake, iso-obliquity and iso-potential depth-of-cut lines guide the procedure such that a condition with the maximum metal removal rate with stable self propulsion could be obtained. Such optimised values for cast iron has been obtained. The procedure can be used for other materials as well.

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INTRODUCTION

A rotary tool is a cutting tool whose cutting edge has a translatory motion along itself such that a fresh portion of the edge continuously passes through the cutting zone. This motion is in addition to the usual motions of cutting speed and feed relative to the workpiece.

MODES OF CUTTING

The cutting edge motion may be given from an external source leading to a driven rotary tool (DRT). Alternatively, the tool may be held in a spindle, freely floating in bearings, with its axis inclined to the workpiece such that the tool rolls freely with the workpiece. This is a self propelled rotary tool (SPRT). There are two versions of mounting the tool. In type I, the orientation is such as to make the tool-end face as the rake face. In type II, the peripheral surface is the rake surface (Fig 1). The scope of type I tool is limited due to space restrictions on the tool spindle design. Type II tool has no such limitation and is therefore more practical. Angle i of rotation of the tool axis in the cutting plane, parallel to the plane including the cutting speed and feed vectors, decides the geometry of type I tool (Fig 1a). In case of type II tool, there are setting angles θ_H and θ_V deciding the geometry of the tool. The tool may be fed in either direction leading to normal and reverse feeds. In normal feed, the rake surface faces the unmachined surface whereas in reverse feed, it faces the unmachined surface of the workpiece.

ADVANTAGES AND DISADVANTAGES

The great advantage[1] of the rotary cutting tool is that it can be made to have a tool life hundreds of times of that of a conventional stationary tool (CST)[2], because the wear is evenly distributed on the long cutting edge. Thus, with a 50 mm diameter tool and 5 mm width of cut, nearly 30 times improvement in tool life is observed due to this reason. Also, for a self propelled tool, the rubbing velocity between the tool flank and the workpiece is reduced due to the rolling action. Zemlyansky[3] has estimated that the improvement in tool life is given by

$$\frac{T_{SPRT}}{T_{CST}} = \frac{2\pi r}{\frac{s}{2} + \cos i \sqrt{2rt}} \tag{1}$$

where T_{SPRT} and T_{CST} are the tool lives of the SPRT and the CST, respectively, r the tool radius, s the feed, t the depth of cut and i the setting angle of the type I tool.

An improvement in tool life upto 30 times can be seen from the above equation. Venuvinod[4] has shown that at higher speeds and feeds SPRT can lead upto 500°C reduction in cutting temperatures. Iyer and Koenigsberger[5] have shown that due to this reduction in temperature, there could be further improvement in tool life by 25 times. The reasons so far given account already for a several hundred-fold increase in tool life. Thus, a high speed steel SPRT can cut at speeds that only a carbide CST can cut. In addition, there are other beneficial effects due to the better coolant access, oxide layer replenishment, etc. The tool can also be expected to give good surface finish due to the large nose radius. Eskelin[6], while milling titanium alloys has obtained rms values of surface roughness as low as 30 micro-inches. The cutting speeds could be raised from 130 to 580 fpm.

SPRT has also been used to replace slideway grinding[7].

A traditional and valid argument against the rotary tool is that it can machine only simple surfaces. However, based on a report on the utilization of machine tools in over hundred engineering industries in UK, it has been shown 1, 11, that upto 30% of volume of metal machined which could be machined conveniently by rotary tools. The application of the SPRT for heat resistant alloys is indisputable. The choice between SPRT and the CST, however, on conventional materials depends on the particular situation.

SPRT may be applied for boring the cast iron casings of electric motors and generators which have simple surfaces. A survey of literature shows that very little information is available on rotary machining of cast iron. Whatever is available is on the use of type I tools. Since type II tools appear to be poised to replace the type I tools, and due to the fact that in boring operations, type II tools are preferred in view of the limited space, it was thought worthwhile to study rotary machining of cast iron.

GEOMETRY OF TYPE II TOOLS

A complete geometrical analysis of type II tools is available in literature[11] only those relationships relevant to the present problem are discussed here.

The geometric analysis of rotary tools requires tedious iterative procedures if the workpiece curvature is small. However, in boring operations the work diameter is much larger than the tool diameter so that an assumption that the work surface is plane does not lead to significant error.

A parameter ω_P is used to specify any point on the cutting edge circle, and the angle subtended at the centre of the cutting edge circle by the portion of the cutting edge lying between point P and the point with maximum coordinate in the direction of the cutting speed. The tool axis is set at angles θ_H and θ_V as shown in Fig 1(b). For convenience, in the following, all length parameters are made dimensionless by dividing by the radius r of the cutting edge circle.

Fig 2 shows the nature of contact between the cutting edge and the workpiece. The point of deepest penetration is F. Points T and S indicate the limits of the contact length. Arcs TS, TF and FS subtend angles ϵ, ϵ_t and ϵ_s at the centre of the cutting edge circle and are measured in the plane of the circle. Thus, while ϵ is the total contact angle, ϵ_t and ϵ_s are its components due to the depth of cut and feed, respectively. Then,

$$\tan \omega_F = \frac{\tan \theta_H}{\sin \theta_V} \qquad (2)$$

$$\tan i_F = \frac{\sin \theta_H}{\tan \theta_V} \qquad (3)$$

$$\gamma_{nF} = \gamma_{nF}' + \gamma_{ns} \quad (5)$$

The depth of cut t_P at any point P on the cutting edge is given by the expression

$$\bar{t}_P = \frac{t_P}{r} = \sin\theta_H (\sin\omega_F - \sin\omega_F) + \sin\theta_V \cos\theta_H (\cos\omega_F - \cos\omega_P) \quad (6)$$

In the case of normal feed, the depth of cut is maximum at point T where ω_P reaches its maximum value. At this point, the angle of obliquity of the cutting edge is also the maximum. For proper chip formation, this obliquity should not exceed a critical value. Based on these considerations, the maximum practicable value of ω_P is 85°. Substituting this value in equation (6), maximum potential value of depth of cut ($\bar{t}_{pot}$) at any setting can be obtained.

Parameters i_F, $\bar{t}_{pot}$ and γ_{nF}' play important role in deciding the optimum setting of the tool. Fig 3, prepared keeping this in view, contains several sets of lines, *viz,*

iso-obliquity lines : each of these lines gives the combination of θ_H and θ_V which keeps i_F (nominal inclination) at a specified value and are obtained using equation (3)

iso-$\bar{t}_{pot}$ *lines* : each of these lines maintains $\bar{t}_{pot}$ at a constant cvalue and are obtained using equation (6) with $\omega_P = 85°$;

iso-rake lines : these maintain the rake angle γ_{nF}' at a constant value and are obtained using equation (4).

The expressions for ω_T and ω_S, parametric angles at points T and S respectively, in terms of setting angles θ_H and θ_V, depth of cut $\bar{t}$ and feed $\bar{s}$, are available in literature[11]. The contact angles are then obtained from

$$\epsilon_t = \omega_T - \omega_T$$

$$\epsilon_s = \omega_F - \omega_S$$

$$\epsilon = \omega_T = \omega_S\, \epsilon_t + \epsilon_s$$

It may be noted that for normal feed, $\omega_T > \omega_F > \omega_S$, whereas for reverse feed, $\omega_T < \omega_F < \omega_S$.

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ROTATIONAL EFFICIENCY

The main advantage of the self propelled rotary tool compared to the driven rotary tool is that it does not need an external drive. For stability of the cutting process, the rotary speed V_t of the cutting edge along itself must be stable and constant. Working on a type I tool, Zemlyansky[9] identified the following zones.

$i < i_1$, no self propulsion ;

$i = i_1$ to i_2, unstable self propulsion ;

$i = i_2$ to i_3, stable self propulsion ; and

$i > i_3$ improper chip formation.

The critical values t_1, i_2 and i_3 depend on the work material as illustrated in Table 1.

Fig 4(a) illustrates the nature of velocity relationships in the cutting and the rake planes. Angle i_{nom} is the nominal inclination angle, V_{wt} is the rubbing velocity vector between the cutting edge and the work surface. Similarly, V_c is the chip velocity whereas V_{ct} is the rubbing velocity between the chip and the tool rake surface. For pure rolling between the tool and the workpiece,

$$V_t = V_w \sin i_{nom} \tag{0}$$

Fig 4(b) shows the variation of the various velocity parameters with the nominal inclination angle.

The rotary speed of self propulsion V_t can be determined by considering the rotational equilibrium of the tool. The angle of inclination i_p at any point on the cutting edge varies along the edge (Fig 2). Thus, there can be pure rolling only at one point, say V, on the cutting edge. On either side of point V, along VT and VS, the slip between toe cutting edge and the workpiece, in the direction of the edge, is in opposite directions. Therefore, the net moment $-T$ due to work-tool rubbing is the difference between the friction moments contributed by arcs VT and VS. The other moments acting on the tool are T due to the forces on the rake surface, T due to friction in the bearings of the set up and T due to thrust component of the cutting force not psssing through the cutting edge centre. The condition of self propulsion is given by

$$\Sigma T = \Delta T_f + T_r + T_{set} + T_y = 0 \tag{11}$$

T_r, T_{set} and T_y are difficult to determine in practice. Konovalov and Gik[8] and Zemlyansky[2,9] have worked on the above lines and have should that when $T_r = T_{set} = T_y = 0$, the nominal inclination angle i_{not} may be taken as equal to i for type I tool and as i_F for type II tool. In practice, however, the tool velocity would be lower than $V_w \sin i_F$ due to the effect of T_r, T_{sit} and T_y. A term rotational efficiency can, therefore, be defined such that

$$\eta_v = \frac{V_t\,(\text{actual})}{V_t\,(\text{nominal})} = \frac{V_w \sin I_v}{V_w \sin i_E} = \frac{\sin i_V}{\sin i_F} \tag{12}$$

where i_V is the angle of inclination at point V of pure rolling in Fig 2 and can be obtained from the measured rotary speed using the equation

$$i_V = \text{arc sin} \frac{V_t \text{ (measured)}}{V_w} \quad (13)$$

In the case of normal feed, increasing t leads to an increase in ω_T whereas an increase in feed leads to a decrease in ω_S. In the case of reverse feeds the effects are of opposite mature. Consequently, in the case of normal feed, a higher depth of cut leads to a better rotational efficiency while higher feeds lowers it. The condition $\omega_T = 85°$, given by the iso-$\bar{t}_{pot}$ lines in Fig 3, puts an upper limit on the improvement in η_v obtainable by increasing the depth of cut. It can therefore be conoluded that the obtainable metal removal rate with a SPRT is mainly constrained by rotational efficiency.

A higher rotational efficiency η_v is desirable since it leads to a higher V_t that leads to a lower rubbing velocity V_{wt} which in turn improves the tool life. Fig 5 shows the observed variation of $\frac{V_w}{V_t}$ with setting angle i of a type I tool for various work materials9. The broken line indicates the ideal variation $\left(\frac{V_w}{V_t} = \frac{1}{\sin i}\right)$. It is seen that cast iron leads to a poorer rotational efficiency and that it has a narrow range $(i - i)$ of self propulsion.

METAL REMOVAL RATE

The metal removal rate is given by the product of the cutting speed V_w, depth of cut t and seed s. In the case of a SPRT the depth of cut t and feed s are restricted by the fact that as their magnitudes are increased, contact angles ϵ_t and ϵ_s also increase. This results in an increase in the net flank friction moment ΔT_f, so that, the rotational efficiency η_v is impaired. This problem is more serious with depth of cut than with feed since it is found that the rate of increase of ϵ with the depth of cut is higher than that with the feed. At present, there is no theory available that can uniquely relate t, s and η_v. This aspect can therefore be studied only experimentally in each situation. It appears that this relationship depends strongly on the work material. Indeed, the poor rotational efficiency observed with cast iron in Fig 5 is a manifestation of this effect.

THE OPTIMISATION PROBLEM

The problem is to select the setting angles θ_H and θ_V such that the metal removal rate ($\bar{t}\,\bar{s}$) is maximised subject to the constraint of adequate rotational efficiency η_v. The quantitative and the qualitative relationships between the various parameters have been discussed in the literature. In particular, it is noted that

(i) θ_H and θ_V influence η_v mainly thorough i_F and ϵ as given by equations (2) to (11) and Fig 3 ;

(ii) the relationship between η_v and ϵ (therefore θ_H and θ_V) cannot be determined analytically, *ie*, essentially, an experimental approach is needed ;

(iii) the rotational efficiency η_v in normal feed can be improved by increasing the potential depth of cut, *ie*, by moving to a higher $\bar{t}_{pot}$ line in Fig 3. But this involves moving to a lower iso-obliquity line which decreases the rotational efficiency ; thus, there exists an optimisation problem ;

(iv) a study of cast iron is of importance, inview of its (a) poor rotational efficiency, (b) small range of self propulsion and (c) economic importance.

EXPERIMENTS

The experiments were done by mounting a 35 mm diameter type II tool on the vertical spindle of HMT mark M2P milling machine. The tool material was HSS. The tool spindle drive gear was removed so that the spindle rotated freely. Cast iron workpieces of size $70 \times 70 \times 100$ mm were clamped on a milling vice. V_w was obtained by the table longitudinal feed and was kept constant at 190 mm/min. The transverse motion of the table provided the feed in the experiments. The depth of cut was noted by mounting a dial gauge on the knee which could be moved vertically. θ_H and θ_V were set by tilting the vertical head by the two angles. A calibrated dial mounted on the tool spindle helped determine the tool rotation and thereby the values of V_t, i_V and η_v. The vice holding the workpiece was mounted on a strain gauge type two component milling dynamometer so that the cutting force P_z and the thrust force P_y could be monitored. The feed force P_x was measured by turning the dynamometer by 90°. Fig 6 shows the force results.

One of the new observations in the experiments was the rotational efficiency η_v could be improved not only by increasing i_F (as is well known) but also by increasing the rake angle, *ie*, by moving on to a iso-v_{nF}' line closer to the origin in Fig 3.

EXPERIMENTAL PROCEDURE FOR OPTIMISATION

Fig 7 illustrates the logic flow chart that has been used to arrive at the values of θ_H and θ_V that maximise $(\bar{l}\ \mathfrak{s})$ without undue loss in η_v. Minor variations in the flow chart are, however, possible provided they are consistent with the following principles.

(i) The metal removal rate $(\bar{l}\ \mathfrak{s})$ can be improved by moving to a higher iso-$\bar{l}_{pot}$ line. This may be done by moving along an iso-i_F line or along an iso-v_{nF}' line. The latter is less desirable since it leads to an undue fall in i_F and therefore in η_v.

(ii) The rotational efficiency can be improved either by moving along an iso-i_F line to a higher iso-v_{nF}' line or along an iso-v_{nF}' line to a higher iso-i_F line. The latter method is used when V_t is unstable or η_v is too poor. The former method is used when the rotation is stable but η_v is desired to be improved without loss in metal removal rate.

The path followed in the case study on cast iron is charted in Fig 3. The first setting (point 1) may be selected arbitrarily since with the suggested logic the optimum setting does not depend on the initial trial setting. However, an analysis of the geometry of type II tools and the relevant literature indicates that θ_V in the range of 20-25° and i_F in the range of 40-50° provides a good starting point. At each setting, a number of $\bar{l}$ (less than $\bar{l}_{pot}$) and $\mathfrak{s}$-combinations are tried and η_v is monitored. The logic flow chart (Fig 7) is used to decide the next setting rationally. The table in Fig 3 shows the values of the best combination of $\bar{l}$, $\mathfrak{s}$ and η_v at some key settings. In this case setting 10 is found to be the optimum with the highest values of η_v and $\bar{l}\ \mathfrak{s}$. The optimum conditions for cast iron are thus found to be $\theta_H = 12°$, $\theta_V = 10°$, $i_F = 50°$ and $v_{nF}' = -16°$. However, if v_{ng} is varied, the optimum values would change. Similarly, if the tool diameter is increased, the relative effect of bearing drag would diminish and it should be possible to achieve a higher values of $(\bar{l}\ \mathfrak{s})$. The optimum values of setting determined above is relevant only to the given tool and the machine. However, a similar procedure may be followed to determine the optimum setting in any other situation.

CONCLUSION

The logic flow chart shown in Fig 7 combined with the sets of iso-obliquity, iso-rake and iso-$\bar{i}_{pot}$ lines in Fig 3 provide an efficient procedure for determining the optimum setting of a type II tool in a given situation. Following such a procedure, a case study on machining cast iron has been described. A new observation that an increase in rake angle leads to a higher rotational efficiency has been made.

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TABLE 1 EFFECT OF WORK MATERIAL ON KINEMATICS OF SELF QROPULSION (NORMAL AND REVERSE FEEDS TYPE I TOOL)

Work Material	Normal Feed i_2, deg	Reverse Feed i_2, deg	Normal Feed i_3, deg
Copper	17	22	65
Pure Zinc	22	—	60
Brass	27	—	75
EI 654	35	—	75
EI 437 A	35	—	75
Zinc with impurities	35	—	75
Steel 30	42	55	80
BT 6	62	70	80