RECENT PROGRESS IN MACHINING WITH ROTARY TOOLS

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SUMMARY

The paper gives the experimental results for type II rotary tools for a wide range of rotary speed ratios. It has been shown that machining with such tools, may under certain conditions, give shear angle values greater than 45° and hence the cutting force component may become zero.

NOMENCLATURE

V_w cutting speed.

V_t rotary speed; speed of the cutting edge along itself.

α_n normal rake angle.

θ_V, θ_H setting angles of the axis of a type II rotary tool in two perpendicular planes (vertical and horizontal).

DEFINITIONS

Rotary tool : A cutting tool whose cutting edge has a motion along itself in addition to the motions of cutting speed and feed relative to the workpiece.

Rotary speed ratio : V_t/V_w.

Chip thickness - compression : ratio of chip thickness to the thickness of undeformed chip.

Chip length ratio : chip length/length of uncut chip.

Normal or reverse rotation–

The rotation of rotary tool is said to be in the normal or the reverse direction depending on whether the rotary speed vector, at a point on the cutting edge; in the zone of contact with the workpiece, has a projection along the cutting speed vector, which is of the same sense or of the opposite sense as the cutting speed vector.

ABBREVIATIONS

SPRT self propelled rotary tool; the rotary tool whose spindle is freely suspended in bearings and which derives its speed entirely by rolling with the workpiece.

DRT driven rotary tool; the rotary tool whose spindle is driven by a seperate drive.

CST conventional stationary tool.

1. INTRODUCTION

Rotary tools have been known for well over twenty years. In comparison with conventional stationary tools (CST), self propelled rotary tools (SPRT) have been conclusively shown to give several hundred times higher tool lives, several hundred degrees centigrade lower cutting temperatures and several times higher rates of metal removal. A significant amount of work in this direction has come from the Soviet

Fifth AIMTDR Conference
Deptt. of Mech. Engg., University of Roorkee.

Union. Since most of such work is little known outside the Soviet Union, a comprehensive list of publications (1 to 52) on the subject is given at the end of this paper.

The only work of significance on the use of driven rotary tools (DRT) is that by Shaw et al[5]. They used an orthogonal DRT (DRT which has its cutting edge at right angles to the cutting speed vector) with $V_t/V_w=2$. It is clear however, from literature that the effect of high rotary speeds ($V_t/V_w>2$) and their combination with various angles of obliquity of the cutting edge have not been systematically studied so far.

In the following report some of the important conclusions, reached in the studies undertaken by the authors with a view to bridge the gap discussed above, are briefly discussed. It will be seen that most of the conclusions are extra-ordinary and far reaching in their practical significance. Detailed analysis of individual aspects is not included for fear of obscuring the significance of the conclusions. It is hoped that the paper would lead to a reassessment of the tremendous potentialities of the rotary tool and the variety of ways in which it can be applied.

2. THE TYPE II ROTARY TOOL

Fig. 1 (a) illustrates the type of rotary tool which has been the subject of extensive studies till recently. The end face of the tool forms the rake surface whereas the peripheral surface forms the clearance surface. For convenience this tool shall be called the type I rotary tool. Fig. 2 shows such a tool in a typical turning application. The important geometric parameters of such a tool are the rake angle, the clearance angle and the angle of obliquity 'i' of the cutting edge which is nominally equal to the inclination of the tool axis to the cutting speed vector as shown in Fig. 1 (b).

Fig. 1(b) illustrates a different type of rotary tool (called the type II rotary tool) which has come into use only recently[37]. In this case the peripheral surface forms the rake surface. Fig. 3. is a schematic illustration of the tool set up in a turnning application. The tool axis makes angles θ_v and θ_h in the vertical and horizontal planes. The rake and clearance angles and the angle of obliquity of the cutting edge are functions of θ_v, θ_h and the height of the tool relative to the axis of the workpiece. The geometry and analysis of this tool are quite involved and are fully discussed elsewhere[57].

The greatest disadvantage of a type I rotary tool is that it leaves little room between the tool axis and the work surface for providing robust bearings. The result has often been a tool spindle of inadequate stiffness leading to instability, poor finish on the machined surface and the consequent under-assessment of the

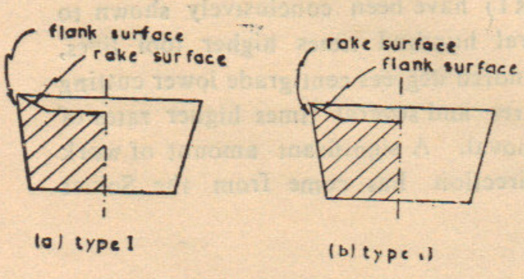

FIG. 1

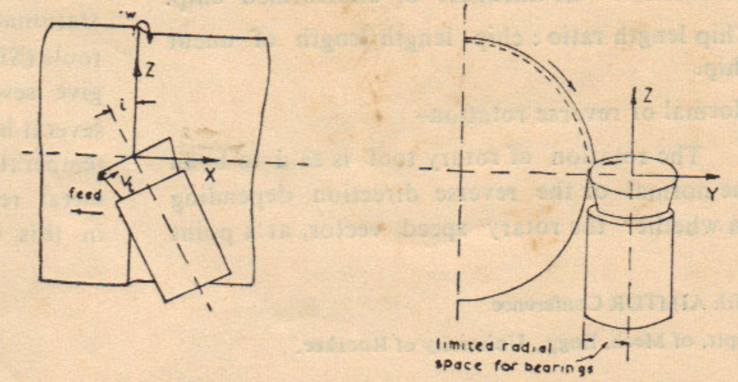

FIG. 2

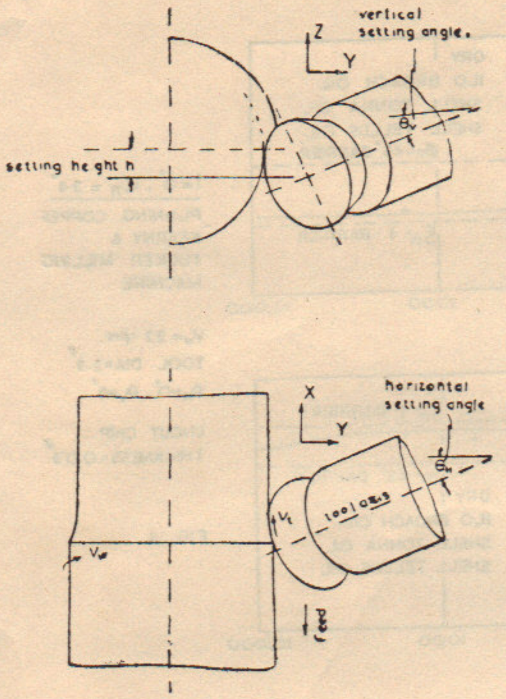

FIG. 3.

capabilities of the rotary tool, in general. With the advent of the type II tool the situation has completely changed. With a type II rotary tool there is ample room to provide any type of bearing system. In fact, the tool spindle can be made as stiff as the machine spindle itself. There is no reason why, with more enthusiasm from industry, rotary cutting should not establish itself as a common machining process.

3. THE EXPERIMENTS

All experiments were conducted with type II rotary tools of diameters ranging from 25 to 65 mm and made of hardend high speed steel. The rigs were so constructed that the rotary speed V_t could be varied over a wide range in either the normal or the reverse directions (see definitions). This variation combined with variation in work speed permitted the rotary speed ratio V_t/V_w to be varied in a wide range (0 to 600). Provision was made to change the angles θ_v and θ_h so that any angle of obliquity of the cutting edge in the range $0-70°$ could be selected. The work materials used were copper, aluminium alloy and mild steel. Limited experments on titanium alloy were also conducted. The first set of experiments consisted of planing operations with a type II rotary tool at very low cutting speeds (0 to 0.2 m/min) on 6.25 mm wide work specimens. The second set consisted of verifying the results at higher cutting speeds (0—150 m/min) by turning and facing operations on a lathe. All chip dimensions were measured. Scratch patterns on the chip underside and the machined surface were observed in order to determine the chip flow angle and the magnitude of rotary speed. Photomicrographic studies were made on chip roots obtained by using a specially constructed quick-stop device using an animal slaughtering gun. A realistic estimation of the normal shear angle could be made from such photo-micrographs. All cutting force components were measured by using specially constructed three component dynamometers using four octagonal rings and strain gauges.

4. MAJOR CONCLUSIONS

The following are some of the major conclusions reached.

1. Chip length ratio as high as 2 can be achieved by adopting very high rotary speeds ($V_t/V_w > 10$) in the normal direction and using high angles of inclination ($i > 40°$).

2. With increasing rotary speed ratio in either direction (normal or reverse) the chip thickness compression attained was close to unity while machining copper. The corresponding maximum normal shear angle was therefore $(45+\alpha_n/2)$. While machining mild steel, however, chip thickness compressions smaller than unity were observed at high rotary speeds. Thus normal shear angle values well beyond 45° could easily be obtained using the rotary tool. Both chip measurements and photo-micrographic studies confirmed the result. Fig. 5 shows

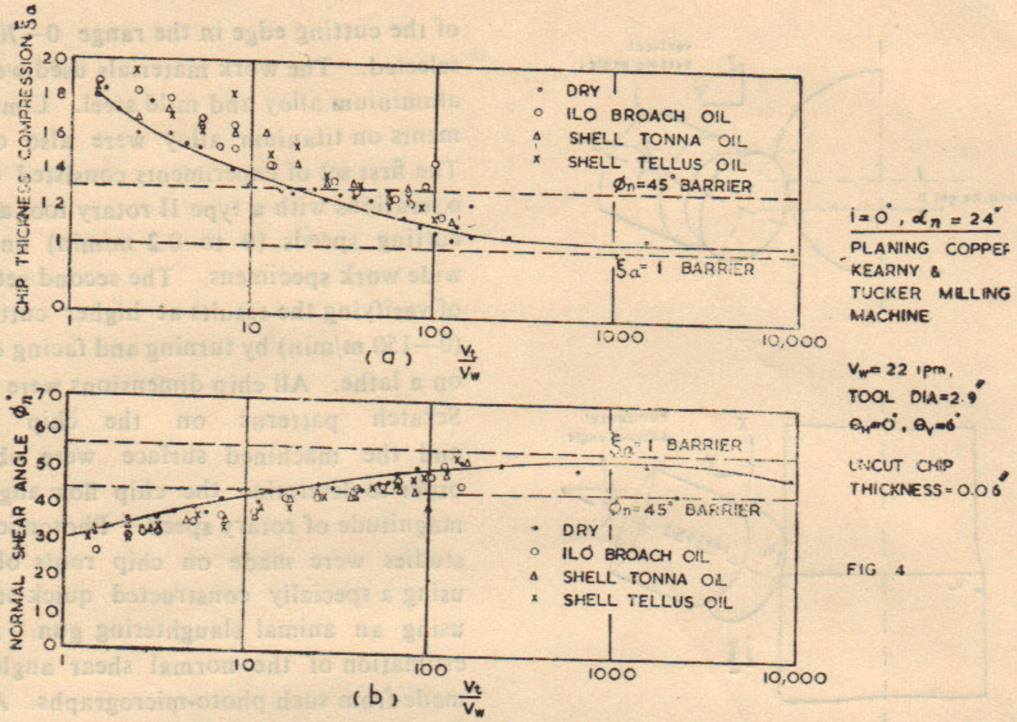

Fig 4

Fig. 5

a typical chip illustrating the high shear angle.

It may be noted here that values of chip thickness compression less than unity have been obtained only in extremely rare situations so far viz. ultra high speed machining, machining with cutting tools vibrating at ultrasonic frequencies in the direction of cutting speed etc. Such processes, when compared to rotary cutting are far too complex to be realised in usual shop conditions.

Further, the above conclusions provide strong evidence against the widely held opinion that while cutting metals the (normal) shear angle "never exceeds 45°".

3. With increasing rotary speed in either direction the level of cutting forces continuously decreases (Fig. 6). Cutting force levele can be brought down to as low as 15% of that obtained with a SPRT, by adopting high rotary speeds ($V_t/V_w > 5$). In the ease of normal rotation components P_y (thrust component i.e. component normal to the machined surface) and P_z (power component i.e. component along the direction of cutting speed) of the cutting force decrease significantly at high rotary speeds. When such high rotary speeds are combined with high angles of obliquity ($i > 40°$), P_z often becomes zero or even becomes negative. The lateral component P_x, however, rarely becomes zero in the case of normal rotation.

4. The level of cutting forces, in general, is the highest in the region of rotary speeds

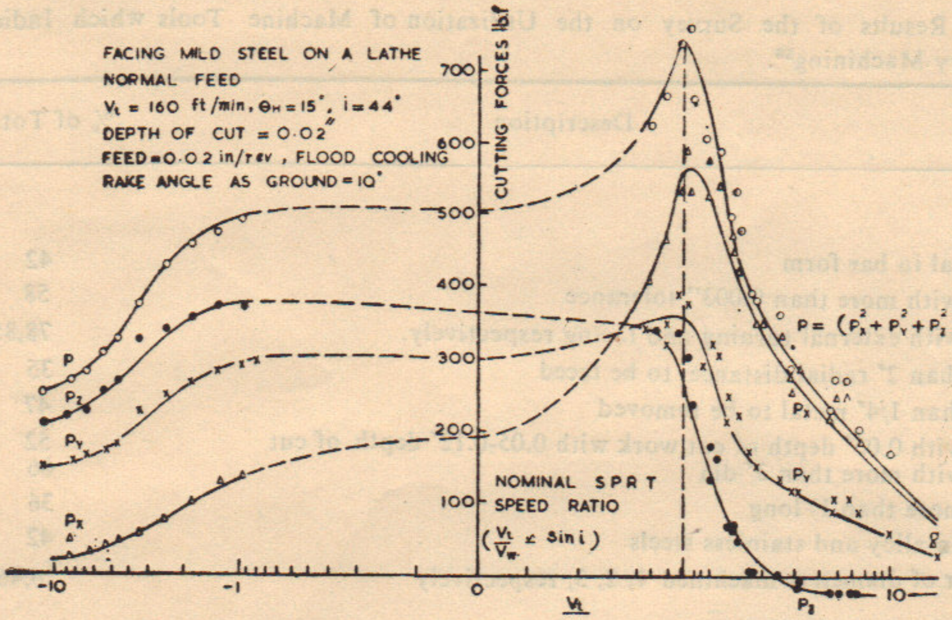

FIG. 6

around that of self-propulsion ($V_t/V_w \approx \sin i$). This has been observed to be mainly due to a peculiar chip-form of triangular cross-section. The analysis of the formation of these triangular chips is complex and, therefore, will be discussed elsewhere. It may, however, be mentioned that it is desirable to avoid these triangular chips since they often lead to very high cutting forces, torn and heavily deformed machined surface and sometimes to tool failure. Work is in progress to investigate ways of avoiding these chips.

5. A NEW METHOD OF ROTARY MACHINING

It has been seen that by adopting high rotary speeds in the normal direction and using large angles of obliquity, the power component of P_z of the cutting force can be brought down to zero. In such a situation, the entire cutting power is supplied by the rotary drive and the main work-drive decomes redundant. To prove the point, rotary machining tests were performed on workpieces, held on running centres at both ends, on a lathe. The cutting process was smooth and the results were encouraging. The cutting forces in such a condition were less than half those obtained with a self propelled rotary tool in similar conditions. The problems associated with triangular chips were also absent.

The commerecial value of the above process need not be stressed. The process is well suited for turning long cylindrical rolls and to some extent in machining large plane surfaces. However, in order to put the new method into effective use, on entirely new type of machine-tools need to be built. Certain new problems like the design of high speed rotary drives, the problems of ensuring constant work speed and feed rate etc. also arise. The authors feel that these are only problems of development, and, when fully developed, the new process will make economic sense.

ROTARY CUTTING AS HOT MACHINING PROCESS

Duing the experiments, it was observed that as the rotay speed was increased (in either direction) the cutting temperture continuously increased. While machining copper the chip did not reach the red hot condition even at the highest rotary speed ratio used. This was pro-

TABLE 1

Selected Results of the Survey on the Utilization of Machine Tools which Indicate the Scope of Rotary Machining[56].

No.	Description	% of Total Work
	LATHES	
1.	Material in bar form	42
2.	Work with more than 0.003" tolerance	58
3.	Work with external turning and facing respectively.	78,85
4.	More than 2" radial distance to be faced	35
5.	More than 1/4" metal to be removed	47
6.	Work with 0.05" depth of cut work with 0.05-0.12" depth of cut	52
7.	Work with more than 3" dia	66
8.	Work more than 1' long	36
9.	Work on alloy and stainless steels	42
10.	Number of diameters machined 1, 2, 3, respectively	26,46,59
	PLANE-MILLING MACHINES	
1.	Work on alloy and stainless steels	33
2.	Work more than 3' long	75
3.	Work more than 1' wide	73
4.	Work with no slots, tapers or machined sarfaces	16
5.	Work with less than 2 slots, tapers or machined surfaces	34
6.	Work with morh than 1/4" metal to be romoved	63
7.	Work with more than 1" metal to be removed	13
8.	Work with less than 0.2 in depth of cut	70
9.	Horizontal facing	71
10	Work with tolerance 0.00"	60

bably due to the high conductivity of copper. While machining mild steel, however, the chips turned red hot for rotary speed ratios exceeding a value of five even at a work speed as low as 0.2 m/min. At higher rotary speed ratios ($V_t/V_w \approx 20$) the chips became white-hot and at still higher rotary speeds there was positive evidence of melting at the chip under-side. This can only be explained by high sliding velocities at the chip tool interface and the resulting high rates of heat generation there. The process can be compared to the phenomena occuring in electric hot machining[53,54] where a current passed through the workpiece and the tool generates large quantities of heat at the chip-tool contact surface. In the new method, however, a given portion of the cutting edge stays under the heat source only for a short period. Further as Barber[55] pointed out recently, at high sliding speeds, more heat is transferred to the softer metal (chip) than to the harder metal (tool) In these respects the new method is superior to electric hot machining. The new technique of hot machining is far superior to other well-known machining techniques in terms of cost of equipment, safety, dimensional accuracy etc.

The various recent developments in the use of rotary tools discussed above, make up a strong case for a complete reassesment of the potential of the rotary tool. It is often argued that the field of the rotary tools in general is limited owing to the fact that it can only machine relative simple surfaces without any grooves, steps etc. While admitting this limitation mention may be made of the results of a recent survey on the utilization of machine tools in U.K.[56] (see Table 1 for selected results). It is amazing to see that despite the limitations on complexity, minimum depth of cut etc. imposed by the rotary tool a vast field exists where a rotary tool, in its various manifestations, can be used to great advantage.

ACKNOWLEDGEMENTS

Dr. P.K. Venuvinod wishes to acknowledge the UNESCO for their financial assistance and Regional Engineering College, Warangal for sponsoring him to a UNESCO fellowship.

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