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# POTENTIALITIES OF ROTARY CUTTING TOOL

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**ABSTRACT**

**Present knowledge regarding the performance of rotary cutting in terms of temperature, forces, shear angle, tool life, metal removal rate and surface finish is briefly reviewed. Areas where the special characteristics of rotary machining can be extended to produce novel machine tools and novel machining techniques are emphasised and discussed on the basis of available data. The proposals include rotary milling, the work propelled rotary tool, rotary broaching and rotary rod shaving, rotary hot machining, cutting with rotary oscillating tools and the prospects of hydrodynamic lubrication in metal cutting. Some of these are based on actual experimental verifications while others are speculations at the present time. The list provides a master plan for future developments in rotary machining.**

## 1. INTRODUCTION

Any process whose cutting edge has a movement (rotary speed $V_t$ ) along itself, in addition to the usual relative movements of cutting speed ($V_w$ ) and feed ($S$), comes under the general name of rotary cutting.

The traditional popular version of a rotary tool is the self propelled rotary tool (SPRT) which derives it's rotary motion essentially from the workpiece by rolling action with it. The tool has all the favourable characteristics of the rotary tool except that it works with low shear angles and high cutting forces. This has since been remedied by externally driving the tool leading to a driven rotary tool (DRT). Phenomenol decrease in forces have been reported by this method.

The traditional geometry of a rotary tool has been that of the type-I tool. This tool has the main disadvantage that it provides limited space for bearings. This has also been remedied by the advent of type-II geometry[1, 2].

Several applications of the rotary cutting already exist. It has been applied in turning, planing, shaping and milling. Most of these commercial applications have used a type-I SPRT. Work is in progress at Regional Engineering College, Warangal, to introduce the type-II geometry and the principle of DRT into applications.

In it's widest ramifications the principle of rotary machining has far reaching significance. It is capable of developing entirely novel machining techniques and stimulating the development of totally new machine tools. It is the aim of this paper to demonstrate the same. The authors hope that the paper would stimulate the interest they desire so that India can have the opportunity to take the lead as a pioneer in this field.

The presence of an effect similar to rotary machining has been reported in many applications by other authors. Reports exist on rotary scratching, rotary rod drawing[3] etc. In each case the advantages claimed include, reduction in frictional forces, absence of built-up edge and the consequent lower forces and better finish.

Some more novel methods of using the rotary principle have been discussed below, arranged in the order of early realisability. Most of the work in this paper is a result of the work-reported in Reference–1. Some have already been briefly discussed in Reference–2. Some are based on experimental data whilst others probably are mere speculations. Some are immediately realisable whilst others have to wait till major advances have taken place in other fields of technology. The list provides a master plan for future developments in rotary machining.

## 2. CHARACTERISTICS OF ROTARY MACHINING

Rotary machining is characterised by the following major advantages.

(*i*) Phenomenal decrease in cutting forces at high rotary speeds (fig. 1). The condition of self propulsion is usually associated with the highest forces.

(*ii*) Lower temperature with an SPRT compared to conventional cutting[4] (fig. 2). In case of a DRT, temperatures fall initially with rotary speed in the medium range and rise when the speeds enter the high range speed[5].

(*iii*) At a particular rotary speed ratio within the zone of medium speeds, the total cutting energy can be reduced by as much as 40% (fig. 3).

(*iv*) Shear angles upto 60° have been achieved at high rotary speed ratios. In fact, only rotary machining, ultra high speed machining and ultrasonic machining[16] have so far broken the "45° shear angle barrier".

(*v*) Increased tool life and higher metal removal rates.

## 3. ROTARY MILLING

Out of the various machining processes the process that best satisfies the requirements of simplicity is plane milling. It is worthwile to examine, therefore, the ways by which rotary machining can be applied in plane milling.

Eskelin[7] has already used a patented milling cutter fitted with 6 type–I carbide-SPRTs to mill titanium alloys with four times increase in productivity. Another similar cutter has been designed at I.I.T., Madras. A possible modification would be to use SPRT tips of type–geometry. The benefit would be the possibility of using reversed feed resulting in the absence of 'triangulation', better surface finish and upto 40% reduction in cutting forces. In any case type-II geometry is better suited for finish machining. Another possibility is to have a cutter similar to the PERA[8] milling cutter with nine type-I tips for roughing followed by one type–II (reverse feed) tip for finish machining. In certain applications *e.g.*, milling of fragile or thin-walled jobs reduction in cutting forces would be especially desirable. A DRT milling cutter is recommended then. The productivity of this cutter (though complex) would be so high that it would demand major improvements in the design of the milling machine itself.

## 4. THE WORK — PROPELLED ROTARY TOOL (WPRT)

An examination of fig. 1. shows that at high rotary speeds ($V_t/V_w > 2$) and high inclination angles the cutting forces $P_z$ rapidly falls to zero and even becomes negative. In other words the tool is driving the work. This is a total reversal of the situation existing with the SPRT. To demonstrate this, mild steel work-pieces were held freely on centres at both ends and machined with a DRT. Encouraging results were obtained. One of the problems that needs special care is to ensure constant $V_t/V_w$ so that feed rate is maintained constant. This could be achieved by using a synchronous WPRT where the workpiece is driven by a low powered unit at the desired speed.

The advantage of the WPRT is that when compared to the SPRT it works at a lower level of cutting force due to the absence of triangulation. Surface finish is also better. Compared to the DRT, the WPRT is far simpler in as much as that it needs only one drive. Unlike the SPRT, the WPRT is not a new tool on an existing machine. It is a new process requiring new designs of machine tool.

## 5. ROTARY BROACHING AND ROTARY ROD SHAVING

The technique of rod shaving is utilised to remove the unwanted material to facilitate the reduction in the size of the available bar stock to the desired dimension, rapidly and economically[9]. The nature of the process is shown in fig. 4.

In electrical copper wire industry the process of shaving by pulling the wire through a die is an established procedure. In steel industry this process has still to have the break through, the main obstacles being excessive die wear and bad finish associatied with formation of built- up edge and high cutting forces. Consequently, shaving of steel beyond a diameter of 15 mm has not been possible. It is suggested that introduction of rotary speed will eliminate BUE and reduce drawing forces. The effect of decreasing cutting forces at high rotary speeds is also useful in this context. Rothman and Sansome[8] have already demonstrated the effect of die rotation on drawing forces in rod drawing. To demonstrate the above in the medium range experiments have been done with a simulated broaching tool in our laboratory, a sketch of which is given in fig. 5.

Experiments were done on specimens of cast iron, mild steel and aluminium. Cutting torque and thrust were measured. Fig. 6 shows the results on cast iron. The remarkable decrease in both torque and thrust is worth noting. Cutting with aluminium was, however, very difficult. This is because the chip is of a ring shape with continuously decreasing diameter. The resultant compressive hoop strains render further cutting difficult. This interaction of hoop strain and cutting strain in section normal to the cutting edge is novel and worthy of further academic interest. While machining mild steel, cutting was totally prevented by the above effect. This could, however, be overcome by making axial slots in the hole so that the periphery is divided into a number of segments. This eliminates the 'ring effect' leading again to reduction in cutting forces. Built-up edge was absent and the finish good.

Experiments on rotary rod shaving are under progress. Higher dividends are expected by the introduction of rotary speed in this case, since the 'ring effect' leads to tensile hoop strains which actually 'aid' the cutting process. It is hoped that steel stock of diameter $>$15 mm can be shaved by this process.

## 6. ROTARY HOT MACHINING

Rotary machining can be classified into two types *viz*., those belonging to "medium rotary speeds" and "high rotary speeds". In the medium range the effect of rotary speed $V_t$ is essentially through modifying the kinematics of chip flow. With increasing $V_t$ chip velocity and the chip flow angle are increased. However, chip flow angle soon saturates at about 70° and further increase in $V_t$ only leads to an increase in slip between the chip and the rake surface. Similarly, the chip length ratio also saturates in the range of 1·5 to 2·3. The transition from medium to high speed range occurs at a value of $V_t/V_w$ between 2 to 10 depending upon the work material and the inclination, angle, the direction of feed and direction of rotation.

In the "high rotary speed" range the major effect of $V_t$ is through easing the friction conditions at the rake surface. Another effect is to increase the proportion of energy consumption at the rake surface relative to that at the shear zone. While machining metals of low conductivity, *e.g.*, steel, there was evidence of considerable heating at the secondary zone. At such low cutting speeds as 8 fpm, the chips became red hot when $V_t/V_w>5$ and turned white hot when $V_t/V_w>50$. There was evidence of melting on the chips.

Another point of interest is the finding of Barber[10] that in the case of heat transfer in a sliding contact, "The greater part of the heat generated by friction should flow into the softer solid... This will cause the softer solid to have higher bulk temperature. The effect will become more noticeable at higher sliding speeds... It is deduced that at high speeds most of the heat flows into the softer solid".

This works in favour of rotary cutting since increasing the sliding speed by increasing $V_t$ results in more heat being transferred to the chip (softer material). This leads to a more efficient use of rotary power. The effect on tool life would be less.

Another promising form of rotary machining is "electric rotary hot machining". The conventional method of electric hot machining, by passing a large current (>300 A) through the tool-chip-work complex has the diadvantage that it heats both the tool and the chips, equally. Consequently, there is an upper limit to the interface temperature that could be induced. If, however, the tool is given a lateral speed $V_t$ the tool could be protected from the heating effects. The upper limit of interface temperature could probably be raised significantly.

An interesting feature of the above process is worth noting. In conventional machining, the entire cutting power is derived from the work drive. One has no control over the specific cutting energy since a variation of any of the parameters cutting speed, feed or depth of cut changes both the metal removal rate and the cutting proportionately. Rotary machining, however, has an additional source of energy in the rotary drive which is unrelated to the metal removal rate. The specific energy can be controlled 'at will', therefore, by varying the rotary speed. Fig. 3 shows a typical variation of tool cutting energy with rotary speed. When electric energy is also introduced, which is again unrelated to the metal removal rate, the control on the process rises enormously. Indeed, it would be very interesting to see how the process would react to variations in the proportions derived from these three energies.

## 7. CUTTING WITH ROTARY OSCILLATING TOOLS

Cutting with oscillating tools has been of an arbitrary nature, as far as the selection of the direction of oscillations is concerned. Oscillations in the feed and speed directions have been tried with varying successes. The most successful has been the introduction of ultrasonic oscillations in the cutting speed direction resulting in chip compression factors close to unity. When one views the problems, with the background of rotary tools, the application of oscillations along the rake surface in the direction of the cutting edge (rotary oscillations) shows promise. Such a direction of oscillation would be unique in as much as that it has no effect on speed, feed or depth of cut. Why this process has not been envisaged so far is easy to see. Cutting with oscillating tools has been veiwed so far only from the back drop of single point tools. Rotary oscillations, are impossible in such a case since during each oscillation, machining would be transferred from the principal cutting edge to the auxiliary cutting edge and vice versa. The conventional rotary tool is a single edged tool. Rotary oscillations are easy to achieve here. Another possibility is to impart linear rotary oscillations to a oblique turning tool along the cutting edge. Technologically, perhaps, this is an easier version.

Speculating on the effects of rotary oscillations one can note the following. At low frequencies, the lateral velocity of the rake surface will be completely transferred to the chip. The chip flow angle will oscillate in unison with rotary oscillations with corresponding effects on the chip velocity. The process is comparable to the range of medium rotary speeds in conventional rotary machining. With increasing frequency, however, the chip would not be able to keep pace with the rake surface and would start slipping relative to it. With further increase in the frequency one can easily visualise a stationary chip freely floating on the rake surface with incidental beneficial effects like the absence of the BUE, absence of adhesion, lower kinetic coefficients of friction and consequent higher shear angles, lower cutting forces, etc. The situation is analogous to that in the case of high rotary speeds. With further increase in frequency (with constant amplitude) more energy will be imparted through the interface zone leading to a situation akin to rotary hot machining.

What would be the special effects of entering the ultrasonic range of vibrations is difficult to perceive at present.

The technological advantages of rotary oscillating tools over conventional rotary tools are easy to note. These include the possibility of a straight edged tool, absence of bearings with the associated clearances, runouts, etc.

## 8. PROSPECTS OF HYDRODYNAMIC LUBRICATION

Hydrodynamic lubrication at the chip tool interface has been considered impossible so far owing to the high normal pressures, (25 to 40 kg/mm$^2$) low sliding velocities and small dimensions of the chip tool contact area. The geometry of the situation can be compared to a pad with high slenderness ratio. The load bearing capacity of such a pad is given by[11]

$$N = \frac{\mu v b^3}{4 h^2}$$

where

$N$ = normal load capacity

$\mu$ = oil viscosity

$v$ = sliding speed (between chip and tool)

$b$ = width of the pad (equal to contact centre)

$h$ = minimum oil film thickness

It is evident that if $N$ could be decreased and $v$ increased sufficiently the prospects of hydrodynamic lubrication are increased. Both these ends could be achieved by increasing the rotary speed sufficiently. It is well known that high rotary speeds lead to drastic reduction in forces (fig. 1). It is, however, necessary that tool run out is considerably smaller than $h$, to maintain an unbroken film. It is evident that in this case, unlike in journal bearing, the film thickness is decided by the process itself.

A decrease in normal pressure and an increase in sliding velocity increase the minimum oil film thickness. The minimum value of $h$ achieved by Foord *et al.*,[12] is of the order of 0·3 micron. When one is able to produce rotary spindles with accuracies higher than 0·3 microns at sufficiently high rotary speeds one can visualise the possibility of hydrodynamic lubrication at the chip-tool interface. And the advantages of hydrodynamic lubrication need no emphasis. It would be a break through in metal cutting.

## 9. ACKNOWLEDGEMENTS

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## REFERENCES

1. Venu Vinod, P. K., Analysis of rotary cutting tools, Ph. D. Thesis, The University of Manchester Institute of Science and Technology, May, 1971.

2. Venu Vinod, P. K., Barrow, G., Recent progress in rotary machining. *Proc.* of 5th All India Machine Tool Design and Research Conference, Roorkee.

3. Rothman, D. and Sansome, D. H., "Rod drawing with die rotation." *International, Journal of Machine Tool Design and Research,* June 1970, P. 179.

4. Venu Vinod., P. K., An investigation to explain and evaluate the performance of a rotary turning tool, *M. Tech,* Dissertation, Indian Institute of Technology, Bombay, 1965.

5. SHAW, M. C., SMITH, P. A. AND COOK, N.H. The rotary cutting tool, *Transactions* of the *A.S.M.E.*, Vol. 74, 1065–1076, August 1972.

6. MASAMI MASUKO AND JUNICHIRO KUMABE, "A few new methods of metal cutting to get a fine surface at low speed." *Bulletin of JSME*, Vol. 2, No. 7. 1969 p. 487–494.

7. ESKELIN, A. F., Rotating carbide inserts machine titanium faster, *Machinery*, 96–89, December 1966.

8. The PERA face milling cutter, *PERA Research Report*, No. 171, August 1967.

9. AVITZUR, B. *Metal forming- Processes and Analysis*, Mc-Graw Hill Book Company, 1968.

10. BARBER, J. R., The conduction of heat from sliding solids, *International Journal of Heat Mass Transfer*, Vol. 13, pp. 857–869 Pergamon Press 1970.

11. TPEI, N., *Theory of Lubrication*, Stanford University Press, 1962.

12. FOORD *et al.*, paper, *Trans.* of ASLE, Vol. 11, 1968, p. 31–43.

## DISCUSSION

*Dr. I. V. S. R. Chary, (Praga Tools Ltd., Secunderabad)* : Your talk on rotary tool was an interesting one. With reference to the sketch, the force $P_2$ was stated to have been measured as a negative value. As this can happen by positioning the dynamometer in the opposite manner could you explain how the force was measured? Also, if it is negative, how does the cutting action in removal of chip from job takes place?

*Dr. Venu Vinod* : A special three component dynamometer was used to measure cutting forces. The component in the direction of cutting speed does become zero or negative. This does not mean no energy is suppied since there is a cutting force along and normal to cutting edge which permits chip formation to take place.

*Dr. G. S. Kainth (I.I.T. Kanpur)*: The confusion created by assigning negative value to the force could have been avoided by assigning inclination angle to the rotary tool which can take care of rotary speed of the tool and cutting speed.

*Dr. P. K. V.* : Theory of oblique cutting has been applied and the rotary cutting process has been explained and we agree with Dr. Kainth. However, the rotary cutting does not just change the resultant force, but causes a drastic reduction in mangitude. In this sense, it cannot be completely explained as a plain oblique process.

*Dr. P. C. Pandey, (Roorkee University)* : Has the dynamic performance of the rotary tool been tested ? Also in the application of carbide tipped tools, there is requirement of particular values of shear angles. And in that context, will the rotary tool allow the use of carbide tipped tools ?

*Dr. P. K. V.* : If you mean chatter as a dynamic stability of the tool, the tool was vibrating a little more than the conventional one. But rotary tool used a higher feed rate.

*Shri M. A. Manan (IIT. Madras)* : With reference to the question of Dr. Pandey, I can say carbide tipped rotary tool was tried out successfully in IIT, Madras. But I want to know about the surface finish obtained in this process.

*Dr. P. K. V.* : The surface finish depends on two things. Firstly, accuracy and stiffness of rotary tool spindle and secondly, the rate of chip formation characterised by the shear angle. This can be solved by type–II rotary tool and the use of a special spindle arrangement.

Secondly, the shear angle can be varied anywhere between 10°—50° at will; the higher shear angle will give better finish.

Thirdly, the large radius of curvature of cutting edge will also contribute for good finish.

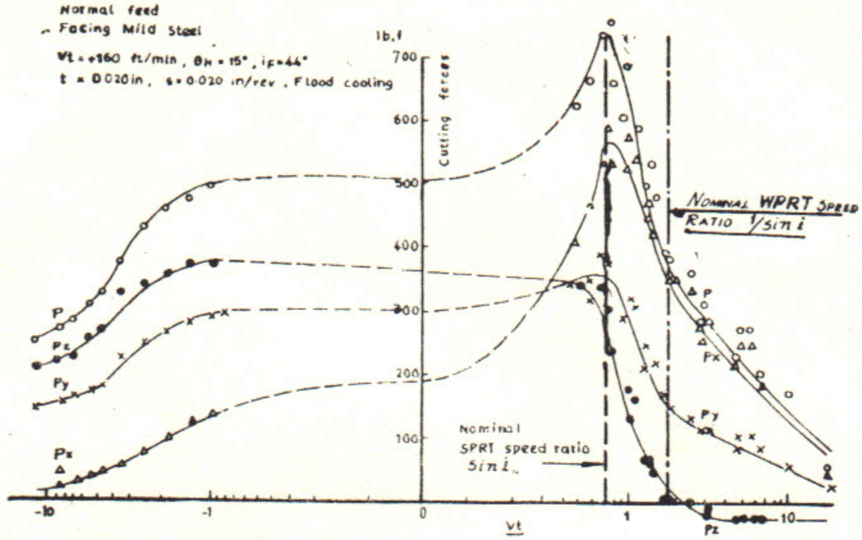



FIG.1. VARIATIONS OF CUTTING FORCES WITH $V_t/V_w$ (Venu Vinod. Ref. 1)

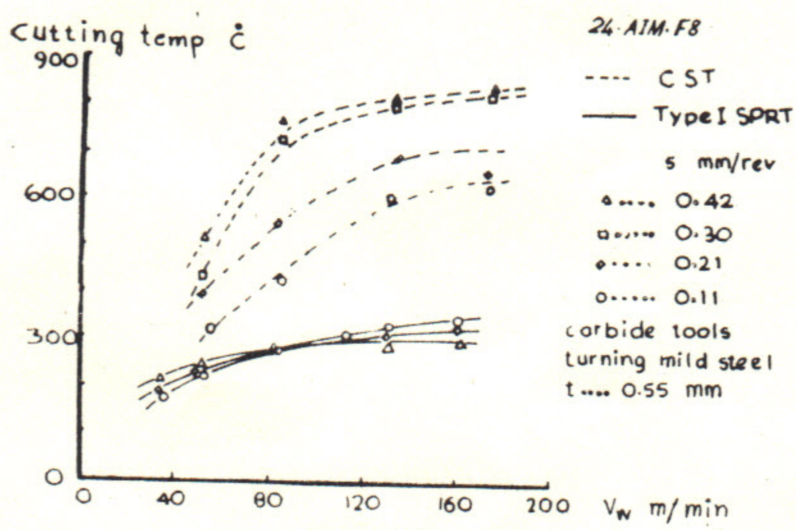



FIG: 2. COMPARISION OF CUTTING TEMPERATURE OF STATIONARY AND ROTARY TOOLS (VENU VINOD REF.5)

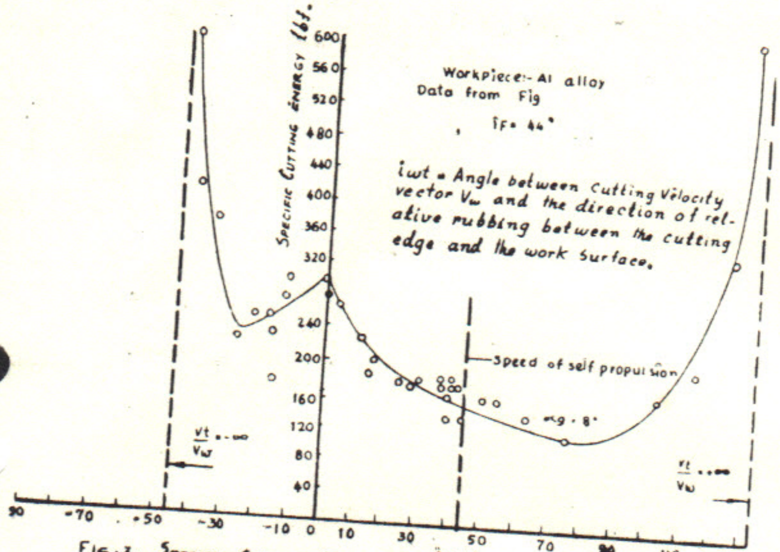



FIG:3. SPECIFIC CUTTING ENERGY VARIATION WITH iwt° (VENU VINOD. REF. 1)

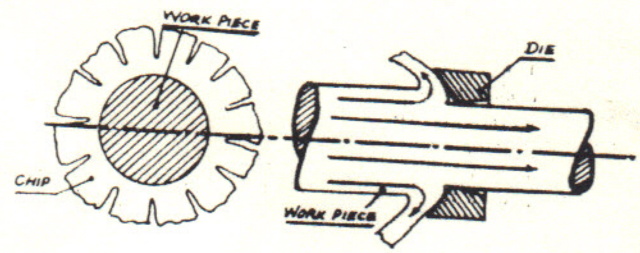



FIG. 4. ROD SHAVING

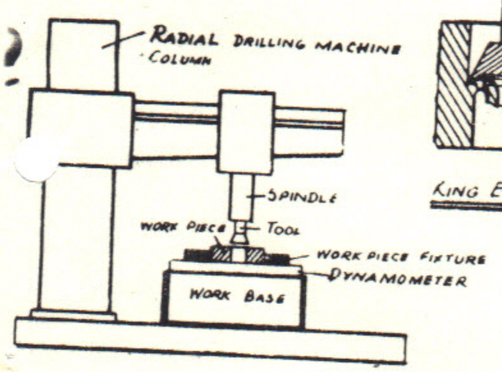
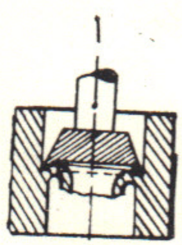



FIG. 5. SET-UP OF ROTARY BROACHING



KING EFFECT

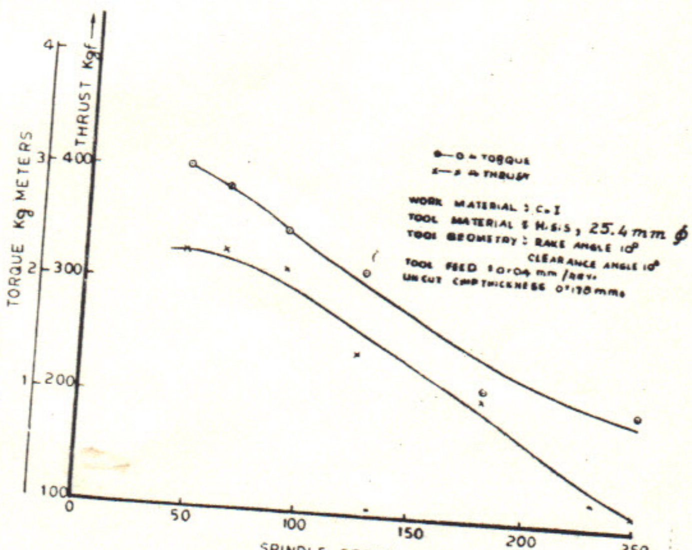



FIG. 6. VARIATION OF BROACHING THRUST & TORQUE WITH SPINDLE SPEED