On the Formation of a Fluid Film at the Chip Tool Interface in Rotary Machining

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Because of the high normal pressures, it is impossible to generate a hydrodynamic film of cutting fluid between the chip and the rake face in conventional machining. At very high cutting speeds the possibility of generating a fluid film of softened or molten chip material exists although it is doubtful if more than a partial film has ever been produced this way. However when materials of relatively low thermal conductivity are cut in a rotary maching process using high speed ratios, the conditions are conducive to the establishment of a continuous fluid film and in the present paper evidence is adduced to show that when mild steel is machined in this way, a fluid layer is easily formed at the chip/rake interface. When the cutting edge obliquity is large, the rotary speed is high and is in such a direction as to cause the chip to deflect towards the line of greatest slope of the rake face, a stream of fluid is drawn out lateral to the chip flow direction and, on cooling, this forms a separate secondary chip. Estimates of the speed of this secondary chip show, as might be expected, that the layer is non-Newtonian.

NOMENCLATURE

b_1	Workpiece width
b_2	Chip width
C_n	Chip-tool contact length measured in the normal plane
F_c	Cutting force component along the direction of Cutting Speed (V_w)
F_{cn}	Cutting force component along the normal to the cutting edge in the cutting plane
$(F_{cn})_f$	Contribution to F_{cn} arising from forces at the tool flank
$(F_{cn})_r$	Contribution to F_{cn} arising from forces at the tool rake
F_{fn}	Component of targential force at tool flank in a direction normal to the cutting edge
F_ℓ	Component of cutting force along the cutting edge
$(F_\ell)_f$	Contribution to F_ℓ arising from forces at the tool flank
$(F_\ell)_r$	Contribution to F_ℓ arising from forces at the tool rake
F_{rn}	Component of targential force at tool rake in a direction normal to the cutting edge
F_t	Cutting force component normal to the machined surface
$(F_t)_f$	Contribution to F_t arising from forces at the tool flank
$(F_t)_r$	Contribution to F_t arising from forces at the tool rake
F_x	Cutting force component normal to F_c and F_t
h_o	Fluid film thickness at entry side of rotary tool
h_1	Fluid film thickness at exit side of rotary tool
i	Angle of obliquity of the cutting edge
ℓ_1	Workpiece length
ℓ_2	Chip length
N_r	Force acting normal to the tool rake surface
N_s	Force acting normal to the shear plane
S_n	Component of shear force at the shear plane in a direction normal to the cutting edge
S_ℓ	Component of shear force at the shear plane in a direction along the cutting edge
t_1	Uncut chip thickness
t_2	Chip thickness
V_c	Chip speed
V_{ct}	Relative velocity between the chip and the tool
V_{sc}	Speed of secondary chip
V_t	Rotary speed
V_w	Work speed (cutting speed)
W	Length of cutting edge in engagement
α_g	Rake angle as ground on a rotary tool
α_n	Normal rake angle
β_g	Clearance angle as ground on a rotary tool
η_s	Angular deviation between the shear force at the shear plane from the normal to the cutting edge in the shear plane
ϕ_n	Normal shear angle

INTRODUCTION

Effective reduction of friction at the chip-tool interface has long been a major objective of metal cutting research. The ultimate one can think of in this regard is reducing friction to practically zero by fluid film lubrication. The survival of such a film, however, is impossible at conventional cutting speeds owing to the enormous normal pressures prevailing. Nevertheless it is well known that at high cutting speeds cutting forces decrease considerably so that the normal pressures the film is required to support are reduced. However, the high cutting speeds usually lead to higher chip-tool interface temperatures so that an externally introduced fluid film tends to degenerate or evaporate.

When cutting speeds are sufficiently high the chip material adjacent to the tool becomes significantly softer and extremely ductile and undergoes such enormous strains that it ceases to reveal a crystalline structure. In short, the chip material in this region, known as the "flow zone", resembles a liquid. In 1964, Schaller [1] attempted to model the flow zone as a Newtonian fluid film of uniform thickness and inferred that a hydrodynamic pressure could not be developed in the flow zone. However, in 1967, Fenton and Oxley [2] included the possibility of reducing friction to zero, due to melting of chip material adjacent to the tool, in their theoretical analysis of machining at super high speeds. In 1968, Desalvo and Shaw [3] suggested that the flow zone is wedge shaped, with its thickness increasing as one moves away from the cutting edge in the direction of chip flow, so that the chip could act as a hydrodynamic pad resting on a wedge shaped fluid film and moving at a sliding speed equal to the chip speed. In fact they viewed the film as a molten layer of the chip material and included considerations of latent heat of melting in their analysis. Using the assumption that the fluid was Newtonian they showed that the fluid film was capable of supporting significant normal loads by hydrodynamic action.

However, unfortunately, the generation of a continuous fluid film at the chip tool interface has never been demonstrated but might occur, possibly, at super high speeds in conventional machining. This is because the heat input at the chip tool interface comes from frictional sliding of the chip on the tool. As the cutting speed is increased so also does the sliding velocity of the chip on the rake so that the rate of heat input into the chip is increased. However, the volume rate of chip material carrying away the heat is also increased in proportion to t[illegible] cutting speed so that the chip tool interface temperature increases rather slowly with incre[illegible] cutting speed. Consequently, melting of the [illegible] even if it occurs, would generally be conf[illegible] portion of the chip tool interface so th[illegible] would still be a considerable portion [illegible] interface in solid-to-solid contact. [illegible] Desalvo and Shaw [3] had to includ[illegible] solid-to-solid contact in their [illegible]

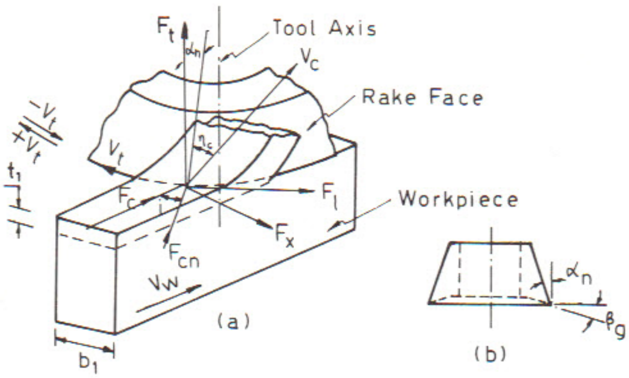

Fig. 1a Rotary Experimental Set Up

Fig. 1b Rotary Tool Geometry

With rotary cutting, however, the situation is completely different. Since rotary cutting is a relatively less known cutting process, a summary of its nature needs to be presented first. Fig. 1a shows an experimental set up for rotary machining of flat workpieces. In this process, the work speed V_w provides the cutting speed. The tool is usually a frustum of a cone (see Fig. 1b) with suitable rake and clearance angle α_g and β_g. The tool spindle may be tilted suitably in two mutually perpendicular planes normal to the machined surface so as to obtain any desired angle of obliquity of the cutting edge i and normal rake angle α_n. The rotation of the tool spindle provides the necessary rotary speed V_t at the cutting edge. The tool may be rotated in the positive or negative directions as shown in the figure. A detailed discussion of the effects of rotary speed on chip formation and cutting forces is available elsewhere [4-7]. It may be noted that the convention used for the direction of positive rotary speed ($+V_t$) shown in Fig. 1a is opposite in sense to that given in earlier publications [4-7]. When i = 0, the effects of positive and negative rotary speed ratios on chip formation and cutting forces are identical whereas the effects are considerably different when $i \neq 0$. Generally speaking, when $i \neq 0$, an increase in rotary speed ratio (V_t/V_w) in the negative direction leads to an increase in the chip flow angle η_c as well as in the chip length ratio (ℓ_2/ℓ_1). The chips are thus usually very long (chip length ratio can exceed unity) and narrow. At very high rotary speed ratios, however, the effect on η_c is reversed so that η_c decreases as speed ratio increases. The chip thickness ratio usually decreases continuously with increasing V_t/V_w i.e. shear angle increases and the cutting force components are reduced considerably. Depending on the work material, cutting force components F_c and F_t are found sometimes to reduce to zero or even to become negative. When the thermal conductivity of the work material is high (eg. aluminium alloy, brass or copper) the minimum chip thickness ratio is usually unity and seldom becomes smaller than unity. When the thermal conductivity is lower (as in the case of mild steel) the chip thickness ratio may reduce to a value smaller than unity.

When the rotary speed is in the positive direction, the effects observed on chip thickness ratio and cutting forces are similar to those described for negative rotary speed ratios. However, the influence on chip length ratio and chip flow angle are opposite. When i >> 0, the chip flow angle η_c and chip length ratio both decrease with increasing V_t/V_w in the positive direction. The chips in such a situation have usually a large width and a short length. The typical trends of t_2/t_1, ℓ_2/ℓ_1 and η_c with changing V_2/V_1 are summarised in Fig. 2.

The main influence of V_t/V_w (whether positive or negative) at the chip tool interface is that it changes the direction and magnitude of the velocity of sliding V_{ct} of the chip over the tool rake surface. As V_t/V_w is increased, the magnitude of V_{ct} is increased appoximately in proportion to V_t so that the rate of heat input is increased. However, the rate of flow of chip material is only marginally increased so that the chip tool interface temperature rises significantly. When the thermal conductivity of the work material is relatively low (as in the case of mild steel) the interface temperature can rise very rapidly with increasing V_t/V_w and at a critical rotary speed ratio a continuous fluid film can be expected at the interface. Evidence is produced in the present paper to show that such a continuous fluid film is indeed formed when machining a low carbon steel at high rotary speed ratios in either positive or negative directions. It will be further shown that the normal loads needed to be supported by the film are quite small so that the survival of the film is encouraged. The paper presents a number of unusual and hitherto unknown phenomena associated with rotary machining and attempts to explain them in terms of the a continuous fluid film at the chip-tool interface. Since all the phenomena discussed above are related to the high chip tool interface temperatures generated when high rotary speeds are used, this process will be referred as Rotary Hot Machining (RHM).

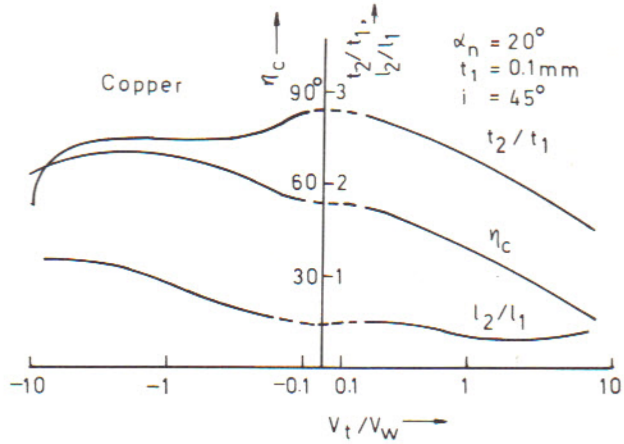

Fig. 2 Influence of Rotary Speed Ratio on the Chip Length Ratio, the Chip Thickness Ratio and the Chip Flow Angle

EXPERIMENTS

The experimental work consisted of machining flat workpieces of mild steel, copper, brass and aluminium alloy at high rotary speeds. The flat workpieces had a length ℓ_1 = 99 mm, width b_1 = 5.9 mm and were about 50 mm wide. The workpieces were mounted on a strain gauge type milling dynamometer which was in turn clamped on the table of a HMT EM-2PU milling machine such that the workpiece length was parallel to the longitudinal table axis. The longitudinal movement of the table provided the necessary work speed V_w. A HSS rotary tool of 69 mm diameter was mounted on the spindle of the universal head of the machine. The spindle axis was tilted appropriately in two mutually perpendicular planes normal to the table surface to obtain the desired magnitudes of i and α_n. The rotational speed of the spindle was set to obtain the desired rotary speed V_t. The uncut chip thickness was controlled by the vertical movement of the knee of the machine and monitored using a dial gauge. Experiments were performed at high rotary speeds in both positive and negative directions. At each condition the dimensions of the chips (length ℓ_2, thickness t_2 and width b_2) and the cutting force components were measured. The length and weight of any secondary chips that were formed were also measured. Whenever necessary the chips were sectioned in the desired planes, polished, etched and studied under a microscope to reveal their microstructure. All experiments were in the absence of a cutting fluid.

EXPERIMENTAL OBSERVATIONS AT HIGH ROTARY SPEEDS AND DISCUSSION

Observations on Aluminium Alloy, Copper and Brass

When machining the above materials at V_w = 0.19 m/min and i = 45°, throughout the range of rotary speed ratio employed (V_t/V_w = -400 to +400) there was little evidence of the build up of a fluid film at the chip tool interface. No significant changes in the general appearance of the chips were noted as the rotary speed ratio was increased. This is attributed to the high thermal conductivity of these materials which could result in the rapid dissipation of the frictional heat flux generated at the interface. At very high rotary speed ratios, in both positive and negative directions, the chip thickness ratio approached unity but seldom became smaller than unity.

Observations on Mild Steel at High Positive Rotary Speeds

When mild steel was machined, however, the situation was completely different from the above. Fig. 3 shows a chip produced while machining mild steel at V_w = 0.19/min, V_t/V_w = -355 and i = 45° and the magnitudes of other cutting parameters and the various measured parameters were as given in Table 1. As expected the chips were short and wide and on measurement were found to be of fairly uniform thickness across their width. The chip thickness t_2 is smaller than the uncut chip thickness t_1. The chip flow angle was approximately equal to zero. Calculations from the chip length ratio shows that the chip speed $V_c \simeq$ 0.175 m/min whereas the rotary speed V_t = +67.5 m/min. Thus, while the chip was moving on the rake surface in a direction normal to the cutting edge, the relative velocity V_{ct} between the chip and the tool rake was approximately parallel to the cutting edge and equal in magnitude to V_t.

During machining, the chips appeared white hot and a number of 'sparks' were seen emerging from the chip tool interface at the point where the tool left the tool. The most striking feature of this process was that a secondary chip was usually found leaving the cutting zone from the exit side of the tool (see Fig. 3). This chip was white hot in appearance as it left the cutting zone but cooled very rapidly a little later. Calculations from the length of the 'secondary chip' indicated that it was moving with a mean speed $V_{sc} \simeq$ 0.2 m/min. This meant that the velocity of the secondary chip V_{sc} was much smaller than the rotary speed V_t but was of the same order as the velocity V_c of the chip. When the weights of the 'primary' and 'secondary' chips were added, it was found to be slightly less than the weight of the uncut chip, the difference being attributable to the loss of chip material via 'sparking'.

Fig. 4 shows a photomicrograph of the secondary chip which reveals a coarse Widmanstätton structure typical of air cooled overheated steels. The structure indicates that the material in the secondary chip could have undergone a temperature of the order of 1300 - 1350°C before its cooling phase.

Fig. 5 shows a photomicrograph of a section of the chip parallel to the cutting edge which reveals a structure strikingly different from that found in the secondary chip (Fig. 4). There is evidence of uneven grain structure with a mean grain size of about 8 µm which is smaller than the mean grain size of 30 µm observed in the uncut workpiece stock. This indicates considerable recrystallisation and that the temperatures in the main chip were also quite high.

The obvious explanation of these observations is that a fluid-like film had formed at the chip tool interface so that the chip-fluid film-tool rake system resembled a hydrodynamic pad. The relative velocity V_{ct} between the tool rake and the chip evidently dragged the fluid film with it so that it left the cutting zone as a 'jet' which on subsequent cooling appeared as the secondary chip. The fact that there was no systematic change in chip thickness across its width suggests that the interface conditions were uniform at any section normal to the cutting edge. This indicates that the fluid film was continuous across the chip width. The presence of the 'sparks' may be explained by assuming that the layer of fluid film immediately adjacent to the tool rake surface was at a temperature approaching its melting temperature. Due to the lower viscosity and higher speed of this layer relative to those of the bulk of the fluid film, it could have been thrown out at a speed approaching V_t thus manifesting itself in 'sparks'.

Observations on Mild Steel at High Negative Rotary Speeds

Fig. 3 also shows a chip formed at a high negative rotary speed when i = 45°. As expected, the chip was long and narrow and the chip flow angle was large. As in the case of machining at high positive rotary speeds, the chips appeared white hot during machining and a number of 'sparks' were found leaving the chip tool interface at the exit side of the tool. However, in contrast to what occured at high positive rotary speeds, here no secondary chip was observed even at the highest absolute magnitude of rotary speed ratio chosen. This may be explained by noting that the chip produced at a high negative rotary speed ratio has a large chip flow angle (about 80°) and a high velocity V_c, unlike the situation obtained when

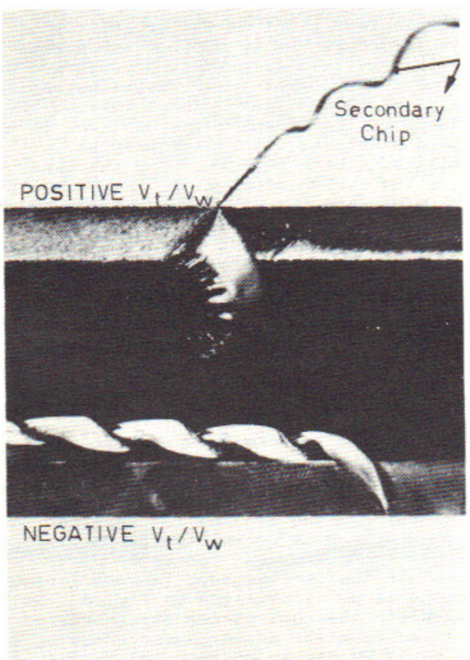

Fig. 3 Comparison of Chips Produced while Machining Mild Steel at Large Positive and Negative Rotary Speed Ratios

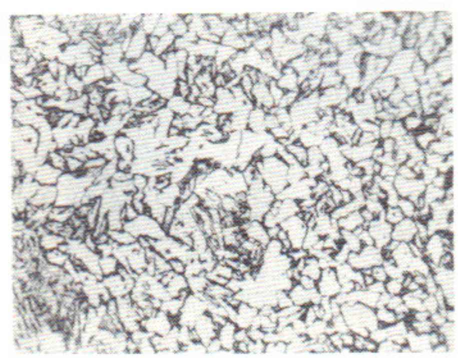

Fig. 4 Photomicrograph of the Cross Section of a Secondary Chip (x800) at High Positive V_t/V_w while Machining Low Carbon Steel

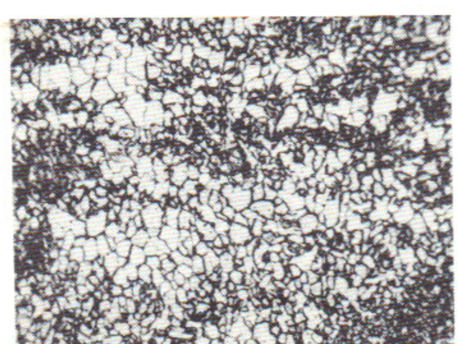

Fig. 5 Photomicrograph of the Section Along a Plane Parallel to the Cutting Edge of a Main Chip (x800) at High Positive V_t/V_w while Machining Low Carbon Steel

a large positive rotary speed ratio is used. Thus, the primary and secondary chips are moving at approximately the same speed and in the same approximate direction (unlike the case in positive rotary speed cutting where the two chips move in mutually perpendicular directions) as they leave the cutting zone. Consequently, it is reasonable to assume that the bulk of the fluid zone and the primary chip had left the cutting zone together and that the fluid zone resolidified on the primary chip. This explanation is consistent with the following observations.

Fig. 6 shows a mild steel chip root formed at a high negative rotary speed ratio at $i = 45^{o}$ and sectioned in a plane perpendicular to the cutting edge. It is seen that the chip thickness ratio (t_2/t_1) is less than unity as observed in the case of high positive rotary speeds. A layer of fine structure is evident in the chip material adjacent to the tool rake surface. Fig. 7 shows a similar chip sectioned in a plane parallel to the cutting edge. A layer of very fine structure (marked F) is clearly evident. The mean grain size in this layer is about 3 μm which is much smaller than the grain size 30 μm of the uncut workpiece stock. It is believed that the fineness of the structure (similar to the 'structureless' flow zone noted by Desalvo and Shaw [3] in high speed conventional maching) is a consequence of the very high temperatures and shear strains experienced by this zone during its formation. It is interesting to note that even the material in the bulk of the chip (zone marked S in Fig. 7) has a refined structure. This indicates that this zone too had been subjected to quite high temperatures and strains. The grain size, however, does not change gradually from zone S to zone F but, instead, there is a sharp boundary between the two zones. It is difficult to decide why the boundary is so sharp and the authors believe this to be the result of zone F being a flow zone comprised of material under viscous shear resembling a liquid whereas the bulk of the chip (zone S) is plastically strained in much the same way as in a conventional chip. The grain distortions observed usually in conventional chips are not evident in either zone S or zone F due to complete recrystallisation.

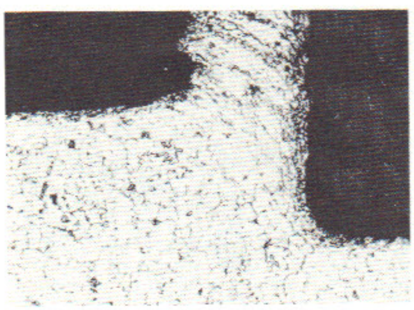

Fig. 6 Photomicrograph of Low Carbon Steel Chip Root Sectioned Normal to the Cutting Edge Obtained at a High Negative V_t/V_w with $i = 45^{o}$ and $\alpha_n = 6^{o}$

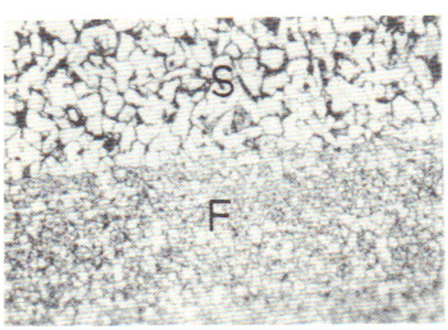

Fig. 7 Photomicrograph of Low Carbon Steel Chip Obtained at a High Negative Rotary Speed Ratio Sectioned Parallel to the Cutting edge, (x1000)

Table 1

Measured and Calculated Parameters Obtained in a Typical Machining Operation at High Positive Rotary Speeds on Low Carbon Steel

Cutting Conditions

Workpiece : low carbon steel
Tool : HSS; diameter = 69 mm
Tool geometry : $\alpha_n = -2.5^{o}$, $i = 45^{o}$
Uncut chip dimensions : $\ell_1 = 99$ mm, $t_1 = 0.25$ m, $b_1 = 5.9$ mm
Cutting speed : $V_w = 190$ mm/min
Rotary speed ratio : $V_t/V_w = +355$

Measured Parameters

Chip dimensions : $\ell_2 = 91.5$ mm, $t_2 = 0.202$ mm, $b_2 = 8.35$ mm
Chip tool contact length : $C_n = 0.4$ mm
Cutting forces : $F_c = 552$ N, $F_t = 257$ N, $F_x = -106$ N
Velocity of secondary chip = 0.2 m/min

Calculate Parameters

Forces due to chip formation : $(F_{cn})_r = 315$ N
$(F_t)_r = -14$ N
$(F_c)_r = 123$ N

The Normal Pressure to be Supported by the Fluid Film

The simplest proof of the capability of the fluid film formed in RHM to support the normal load acting is that a fluid film was indeed formed and that it did support the normal load. Notwithstanding this it is useful at this stage to check whether the fluid film can support the normal loads observed in high rotary speed machining. For this purpose, calculations have been performed for the case of machining a low carbon steel at $V_w = 0.19$ m/min, $V_t = -67.5$ m/min and $i = 45^{o}$ for which the magnitudes of the various measured parameters are given in Table 1. It is seen that the measured cutting forces are quite small. To estimate the normal pressure at the chip tool interface it is necessary first to separate the edge forces occuring at the tool flank from the measured overall cutting force components. In a conventional cutting process the separation of these edge forces is an involved task. However, the procedure is a straight forward one in the case of machining with high rotary speeds since, in this case, the sliding velocities V_{ct} and V_{wt} (between the chip and the tool at the rake surface and the workpiece an tool at the flank surface respectively) are, for all practical purposes, equal to the rotary speed V_t. It is reasonable to assume then that the components of friction force (F_{rn} and F_{fn}) at the rake and flank surfaces in a direction normal to the cutting edge have negligible magnitudes. The force system in a plane normal to the cutting edge in such a situation is unique and is as illustrated in Fig. 8. It is easy now to calculate the cutting forces associated with chip formation from the measured forces using the equations given in the Appendix. The results of the calculations are shown in Table 1.

It is seen that the normal load N_r acting on the tool rake is about 322 N whereas the chip-tool contact area is 0.4 x 8.35 mm^2 so that the mean normal pressure to be supported by the fluid film is 94 MPa. Desalvo and Shaw [3] have analysed the hydrodynamic action of the fluid film in an example of conventional orthogonal cutting and suggested that the fluid film is able to support a normal pressure of 300 MPa when the cutting speed is 183 m/min and the chip thickness ratio t_2/t_1 is 2.17 so that the chip sliding speed is 84 m/min. It is reasonable to expect then that the fluid film in the example of rotary machining being discussed would be able to support a pressure of 96 MPa when the chip-tool sliding speed is 67.5 m/min.

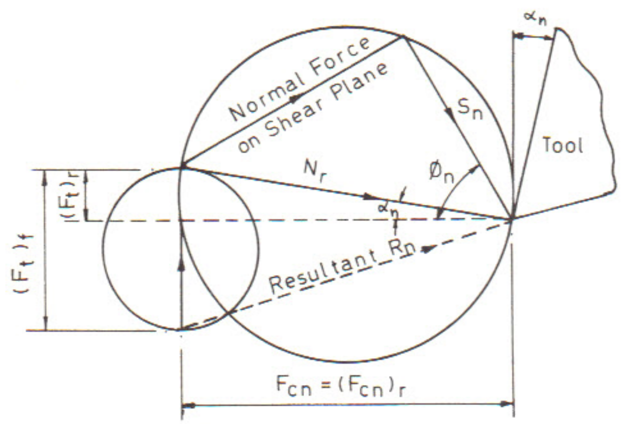

Fig. 8 Force Diagram at High Rotary Speed Ratios (assuming F_{rn} = F_{fn} = 0) in a Plane Normal to the Cutting Edge

Despite the apparent consistency of the above argument, one cannot rely totally on the quoted figures since the calculations of Desalvo and Shaw [3] were based on the assumption of a Newtonian fluid film which will be shown later to be unreasonable.

A Schematic Model of Fluid Film in Rotary Hot Machining

Keeping in view the various observations discussed above, it is now possible to construct a schematic model of the fluid film occuring in rotary hot machining. Fig. 9 illustrates the suggested model of the chip-fluid film-tool rake system. The chip is viewed as a hydrodynamic pad, the length of which is equal to the length of active cutting edge W sliding on the tool rake surface in a direction practically parallel to the cutting edge, the magnitude of the sliding speed being very nearly equal to the rotary speed V_t. The film thickness is assumed uniform in a direction normal to the cutting edge (see Fig. 9a). To generate hydrodynamic action, however, the film will have to be wedge shaped in the direction of sliding with its thickness decreasing from h_1 at the entry side to h_o at the exit side (see Fig. 9b). It is easy to see now the origin of the secondary chip. The rotary speed V_t causes intense shear within the fluid film and tends to throw the film out as a jet which results in a secondary chip in the case of negative rotary speeds. In the case of negative rotary speeds, however, the main chip and the fluid jet are moving approximately in the direction of the cutting edge (η_c ~ 80°) at comparable speeds (about twice V_w) so that the secondary chip does not have a separate existence.

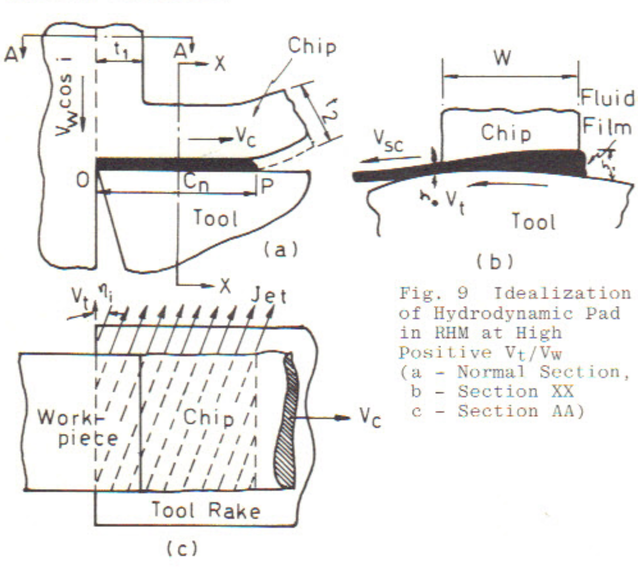

Fig. 9 Idealization of Hydrodynamic Pad in RHM at High Positive V_t/V_w
(a - Normal Section,
b - Section XX
c - Section AA)

Consider at this stage the inferences that follow if one assumes that the fluid film behaves like a Newtonian fluid. If the fluid film is indeed Newtonian, the velocity gradient across film thickness should be uniform so that the mean velocity of the fluid leaving from the exit end of the wedge in Fig. 6b should be nearly equal (ignoring side flow) to half of the sliding speed of the pad. Since the sliding speed $V_{ct} \approx V_t$, in the example illustrated in Table 1, the fluid jet should have had a velocity equal to about 33 m/min. However, the actual mean speed of the jet calculated from the length of the secondary chip is only 0.2 m/min which is nowhere near the estimated figure of 33 m/min. It is thus clear that modelling the fluid film as a Newtonian liquid of uniform viscosity leads to conclusions which are contrary to experimental observation. The more likely explanation is that the viscosity of the film would increases significantly as one moves away from the tool rake towards the bulk of the chip across the film thickness so that the film, when viewed as a whole, would resemble a non-Newtonian liquid.

Consider now the geometry of the idealised hydrodynamic pad illustrated in Fig. 9. The pad may be idealised as a rectangular pad of length W equal to the length of the cutting edge in engagement and of width equal to the chip tool contact length C_n. As shown in Fig. 9a the film is open to the atmosphere at point P but abruptly ends at the cutting edge (This implies that the film covers the entire chip-tool contact area but does not extend into the contact zone at the tool flank. (The latter condition was sometimes observed by the authors but the tool wear in such cases was too rapid to make any measurements possible.) One can then expect significant side flow only at point P but no side flow at the cutting edge. Thus the pad is essentially an asymmetric pad. For the purposes of analysis, the pad may be viewed as one half of a symmetric pad of dimensions $2C_n$xW. Usually W >> C_n so that in practice the pad is a very narrow pad (similar to a ski-like shoe) involving significant magnitudes of side flow in a direction normal to the pad sliding speed (i.e. along the normal to the cutting edge in the rake plane). Consequently, the direction of the fluid jet would be at an angle η_j to the cutting edge as shown in Fig. 9c. The fluid jet, as it is squeezed out from under the chip, would cause a viscous drag in the direction of the jet. Since the jet is at angle to the cutting edge this viscous drag would have a component normal to the cutting edge which tends 'pull' the chip up the rake face. In short, the friction force experienced by the chip in a direction normal to the cutting edge at the chip tool interface would be opposite in direction to that observed in conventional cutting. As a result the chip should be in a state of tension rather than a state of compression as observed in conventional cutting. This perhaps explains, at least partly, why the chip thickness ratio could be less than unity (compare the chip thickness to uncut chip thickness in Fig. 6) when a low carbon steel is machined at high rotary speeds. It is interesting to note further that while machining copper or brass or aluminium alloy where no fluid film was observed the chip thickness ratio seldom became smaller than unity.

Consider next the origin of the fluid film. When the rotary tool first engages the workpiece and a chip is initiated, there is considerable solid to solid contact and the friction is high. Owing to the high friction and high sliding speeds at the interface and the fact that the chip flow rate is small in comparison to the rate of heat input, the interface temperature rises rapidly. If the thermal conductivity of the work material is relatively low (as in the case of mild steel) the interface temperature could reach a value sufficiently high to cause the layer of chip adjacent to the tool rake to behave like a fluid. Once a fluid film is formed the heat flux generation ceases to occur by frictional sliding but instead occurs by viscous shear within the fluid film. In such a case the conventional method of calculating the chip-tool interface temperature by the application of the theory of moving heat sources between sliding solids becomes impermissible. To confirm this point, the authors applied the theory of moving heat sources to the data described in Table 1 (assuming the chip to be moving over the rake heat source at a velocity V_c and the tool moving on the same heat source in a perpendicular direction at velocity V_t) and obtained an estimate of mean interface temperature equal to 127°C which is totally inconsistent with observation of white hot chips, fluid jet and sparking. Further, calculations on the heat partition coefficient at the chip-tool interface gave a resultant rate of heat flux entering the chip from the interface of such a magnitude as to be capable of melting the chip 5.8 times over. The authors consider the failure of the theory of moving heat sources based on solid-to-solid contact as yet another evidence in support of the view that the chip tool interface in high rotary speed machining does not consist of solid-to-solid contact but is actually a fluid film.

CONCLUSION

It has been shown that when machining materials of relative low thermal conductivity (for example, low carbon steel) at high rotary speed ratios, a fluid film can be formed at the chip tool interface. When employing high positive rotary speeds combined with large cutting edge obliquities, the fluid film emerges from the cutting zone as a fluid jet and forms a secondary chip that is quite distinct from the main chip. In the case of high negative rotary speeds, the previous existence of fluid may be inferred from the layer of very fine structure in the chip material adjacent to the tool rake surface. The presence of the fluid film explains the unusually low cutting force levels and small chip thickness ratios found when machining at high rotary speeds resulting in rotary hot machining. Observations on the nature of the process indicate that it is reasonable to view the chip-fluid film-tool rake surface as a hydrodynamic pad. The normal pressures experienced by the pad are quite small so that the survival of the film is ensured. It is shown that the assumption of a Newtonian fluid film leads to results contrary to experimental observation.

The major interest in Rotary Hot Machining lies in the fact that, to date, it is the only (yet simple) method of achieving a continuous fluid film at the chip tool interface in metal cutting. Thus it paves the way for studying the condition of chip formation associated with near zero friction at the chip-tool interface.

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APPENDIX

Note : see nomenclature for the explanation of the symbols used in the following.

The measured force components F_c and F_x can be resolved suitably to obtain the force components F_{cn} and F_ℓ. We wish to obtain the force components $(F_{cn})_r$, $(F_t)_r$ and $(F_\ell)_r$ contributed by chip formation from the measured forces F_{cn}, F_t and F_ℓ after separating the force components $(F_{cn})_f$, $(F_t)_f$, $(F_\ell)_f$ arising from the tool flank.

To achieve this, the following equations are easily obtained from the force diagram in Fig. 8.

$$(F_{cn})_r = F_{cn} \tag{A.1}$$

$$(F_t)_r = -F_{cn} \tan \alpha_n \tag{A.2}$$

$$S_n = \frac{F_{cn} \cos (\phi_n - \alpha_n)}{\cos \alpha_n} \tag{A.3}$$

If η_s is the angular deviation of the shear force vector acting at the shear plane from the normal to the cutting edge in the shear plane, we have

$$S_\ell = S_n \tan \eta_s \tag{A.4}$$

Now, for equilibrium of forces acting parallel to the cutting edge on the chip

$$(F_\ell)_r = S_\ell \tag{A.5}$$