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CHIP BREAKING FOR AN AUTOMATED ACCURATE TURNING SYSTEM

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ABSTRACT

Based upon a survey of chip breaking information, the various methods have been evaluated for application to automated accurate turning systems. Many chip breaking methods work well on shafts or cylinders but fail to break chips for an entire inside or outside contouring cut. Many metals produce straight or snarled chip forms at small depths of cut, feed rates, or moderate surface speeds. These chip forms can be a cause of workpiece and tool damage. Such forms also interfere with on-machine gaging, part transfer, and tool change. Often the chip wraps around the tool holder and is difficult to remove even in manual operation. Computer analysis now makes it possible to get the most out of each type of chip breaking system. Reliable chip breaking is urgently needed for automated systems, especially those operating in an unmanned mode.

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INTRODUCTION

The objective of this report is to examine the current status of chip breaking technology, describe the methods, and assess the relative benefits for automated turning applications on a variety of materials. Reliable chip breaking is a must for automated accurate systems. Failure to break chips can result in: damage to workpieces, damage to tools, hazards to operators, and jams which hinder reliable automatic part loading, and transfer. A complete literature survey has been made covering about 300 references. A more limited selection of papers is listed. The methods of chip breaking have been broadly categorized by the following physical mechanisms: (a) chip fracture near the tool tip, (b) mechanical cutters or process interrupters, and (c) chip capture and control devices. Historically, most of the effort has concentrated on fracture methods, some work has been devoted to ways to interrupt the cutting process momentarily or to chop the chip, and almost no attempt has been made to develop capture devices. This paper concentrates on turning operations, but some of the literature is concerned with milling, drilling, and other processes that produce chips. Very little data exists concerning chip breaking for fine finishing cuts.

STATUS OF UNDERSTANDING THE CHIP MAKING PROCESSES

Analysis of machining or the cutting of materials based on the principles of physics has progressed to a rather mature state in which finite element models (FEM) on computers can simulate cutting. Work in references 1, 5, 9, 11 and 61 represent such analyses. The results agree rather well with observations even for a crude material properties code. Figure 1 represents an FEM predicted chip being formed. The method has the possibility of predicting the state of strain throughout the chip. It can also do rather well in determining temperature distributions, the shear angle, and the influence of external forces such as those produced by chip breaking systems. The ease with which chips can be broken depends upon the state or hardness of the material as well as the thickness. Some estimates in the literature for steel are that the ultimate strength of the chips are 1.5 - 2 times greater than the workpiece(25). The FEM analysis can be extended to evaluate those quantities which harden or conversely could soften or anneal the chip along with interactions with forces needed to break the chip. For some of the hazardous or expensive materials, this type of analysis is urgently needed as an alternative to numerous experiments. Most of the present limitation of the FEM analysis is: (a) the material properties data is inexact, and (b) the method has not yet been applied specifically to chip breaking including the external forces and the quenching of hot chips with the coolant where used. An extension of the analysis to chip breaking, predictions for

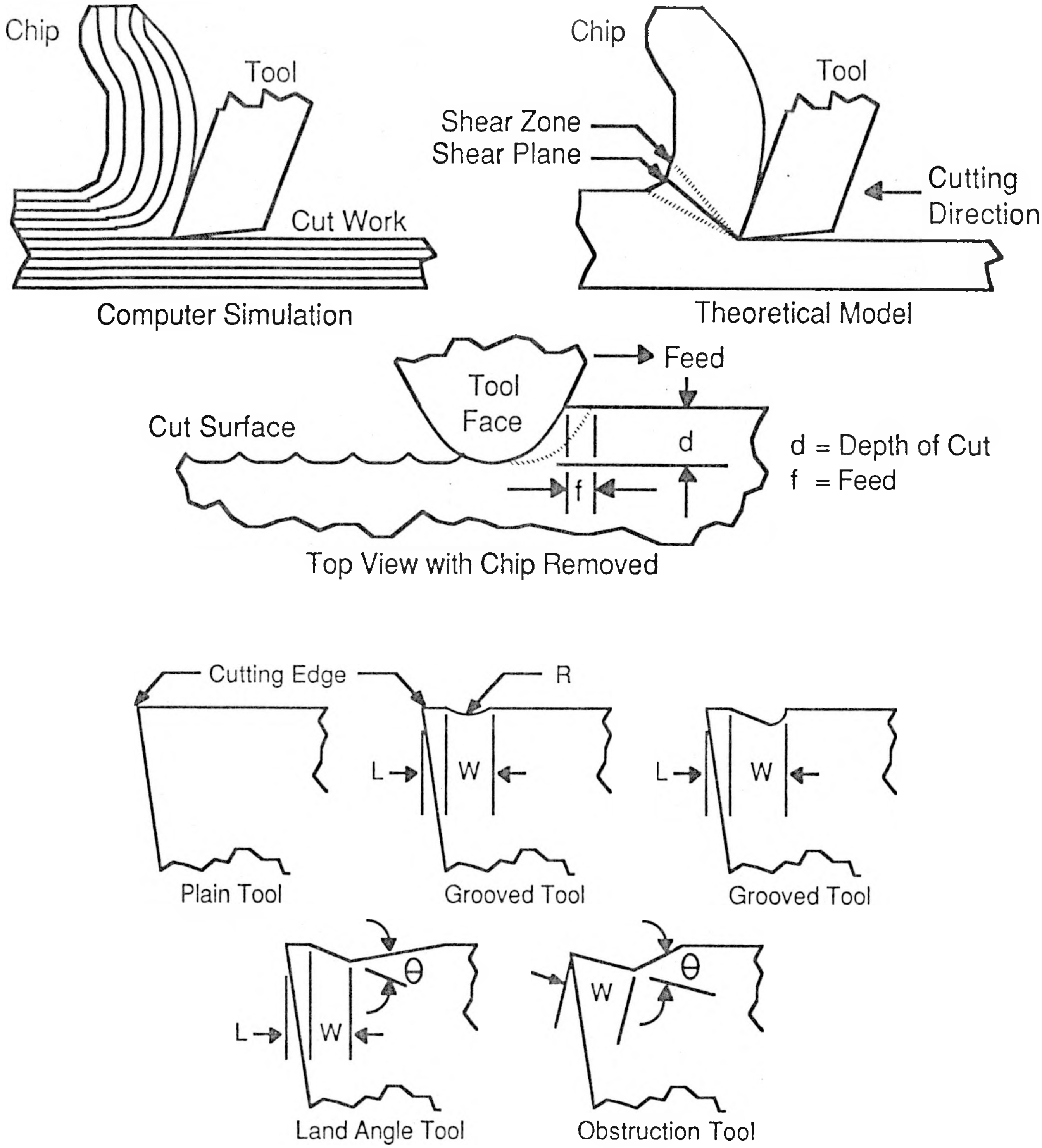

Figure 1. Cutting Model and Tool Designs

specific materials, and a few verification tests are now needed. Figure 1 shows several styles of passive chip breakers (10). Two effects are attributed to the breaker. First is a lifting which produces a moment at the shear plane and reduces chip to tool friction and the curl radius. Second, some breakers produce varying amounts of thrust on the shear plane. Most work has dealt with rather large depths of cut, and at least in these cases, the limiting feed rate to break chips is proportional to the chip radius of curvature (10,11) or the ratio of curl radius to chip thickness. Some conditions for crack formation in chips have also been described which would alter the ease of breaking chips as well as the role of coolants (9). The shear angle has been shown to relate to the work hardening and tool to chip friction both of which reduce the angle. A small shear angle corresponds to a thicker chip for the same depth of cut. Thus some guidance is provided in designing systems to break chips at small depths of cut and feed rate, but testing is needed. Eight forms of chips are generally described in the literature. Four of these, the intermittent snarl, the short helix, the full circle, and the half circle are considered good forms (10). However, for an automated accurate turning system, the intermittent snarl has some potential for part surface and tool damage when cutting shapes such as spheres, particularly for inside hemispherical cuts. Thus, only the last three forms are desirable for such an application. A further result of chip breaker use is that the combination of a land angle, a groove, and a rake angle makes a composite effective rake angle. This in turn alters the shear angle, and chip curl radius. Thus the chip breaker does more than exert a bending moment. Also, in general the smaller the land width, the higher the tool wear rate.

METHOD DESCRIPTION

I. Chip Fracture Methods

A. Passive mechanical fracture.
This means of breaking chips places an obstruction in the chip flow path or a groove backed by a ridge. In each case the ridge produces a bending moment which fractures the chip as illustrated in Figure 2, or causes curvature such that the chip curls into the tool or workpiece and the contact force causes it to break. Equipment required for the method is either tools with obstructions or grooves formed on them or else small clamped-on breakers on the tools. (1-64) Some tools even have multiple parallel grooves to extend the range of depths of cut.

B. Active mechanical fracture.
The principle is like the passive fracture system. As the feed and cut depth change in making contoured parts, and the cutting edge changes its effective angle to the direction of tool motion across the workpiece, the location and orientation of the chip breaking barrier needs to change. An active mechanical system achieves the needed positioning. See Figure 3. Active systems can also compensate for the

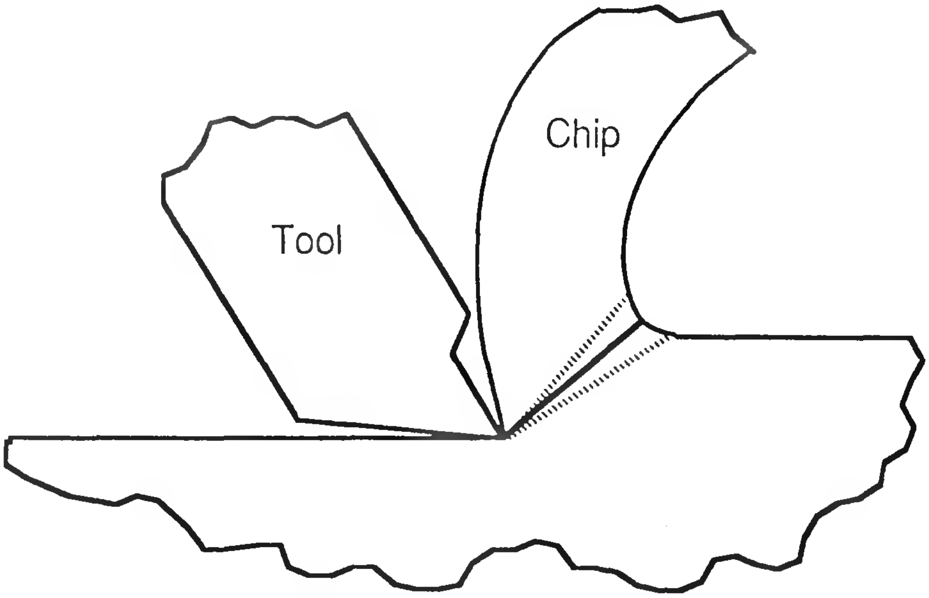

Figure 2. Mechanical Chip Breaking

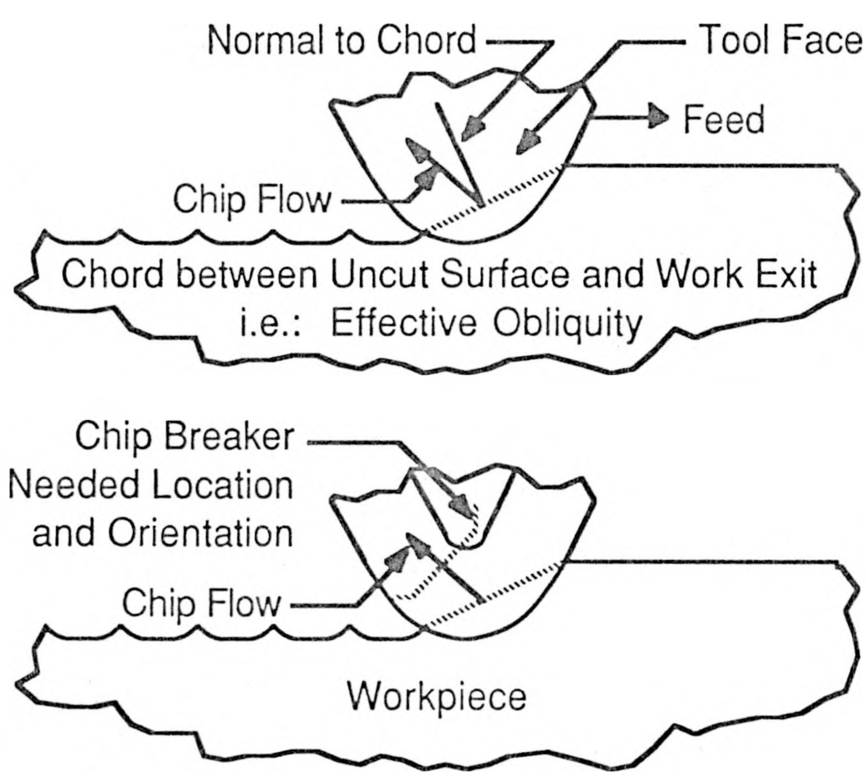

Figure 3. Needed Chip Breaker Positioning

influence of tool wear on chip breaking by repositioning the breaker the proper distance from the worn edge. Needed equipment resembles the clamped on passive systems plus complex devices to position the breaker ridge (7,35,65-67). One paper reports using a roller type obstruction to deflect the chip to one side (57).

C. Active hydraulic fracture. Normal bending force.
A hydraulic jet directed between the chip and the tool rake face results in a normal bending force bending it away from the tool's rake face. The breaking force depends on the unbroken chip length, the fluid pressure, the chip area, and the required breaking stress. When the local stress reaches a fracture level, the chip breaks. The pressure only lifts the chip but produces no thrust force. Conditions producing larger bending moments make shorter chips. Ductility also influences chip lengths. Figure 4 shows the hydraulic reaking principle. The aim direction of the jet is important because the chip is more vulnerable to fracture in some directions. The chip form is usually a half circle or crescent. Needed equipment consists of a high capacity high pressure pump, high pressure hoses and lines, orifices for flow control, manifolds to deliver fluid to the tool station and nozzle systems at the tool. Hydraulic pressures can be as low as 1200 psi and may be over 6000 psi, while the largest commercially available flow rate is about 9 gallons per minute. Tests show that flow rates as low as one gallon per minute per active tool may be adequate for finishing conditions with some materials. (68-72)

D. Active hydraulic fracture. Transverse bending force.
The principle is the same as with the normal bending force except that the bending occurs from side to side. This method has been successfully applied using pneumatic pressure or vacuum for the very fine chips produced in diamond turning. It has also worked for some alloys which make chips difficult to break any other way. Equipment may not need to produce large pressures and flow quantities. High pressure gas or vacuum equipment, sometimes may be used for very fine cuts as in diamond turning and is also useful for removal of chips from the work zone and with chips from brittle materials.

E. Active cryo-hydraulic fracture. Normal bending force.
The principle is the same as method (C) above except that a refrigerant gas is injected into the hydraulic stream to control temperature and perhaps apply the jet pressure more effectively to the underside of the chip. Cold gas may alter the material properties in the shear zone since these are temperature dependent, which can change the shear angle and chip curl radius perhaps beneficially to chip breaking. The chip form is usually a half circle or crescent as in the normal hydraulic system (C). No references discuss the cold gas but those describing the normal hydraulic method do apply. Necessary equipment resembles that in the hydraulic

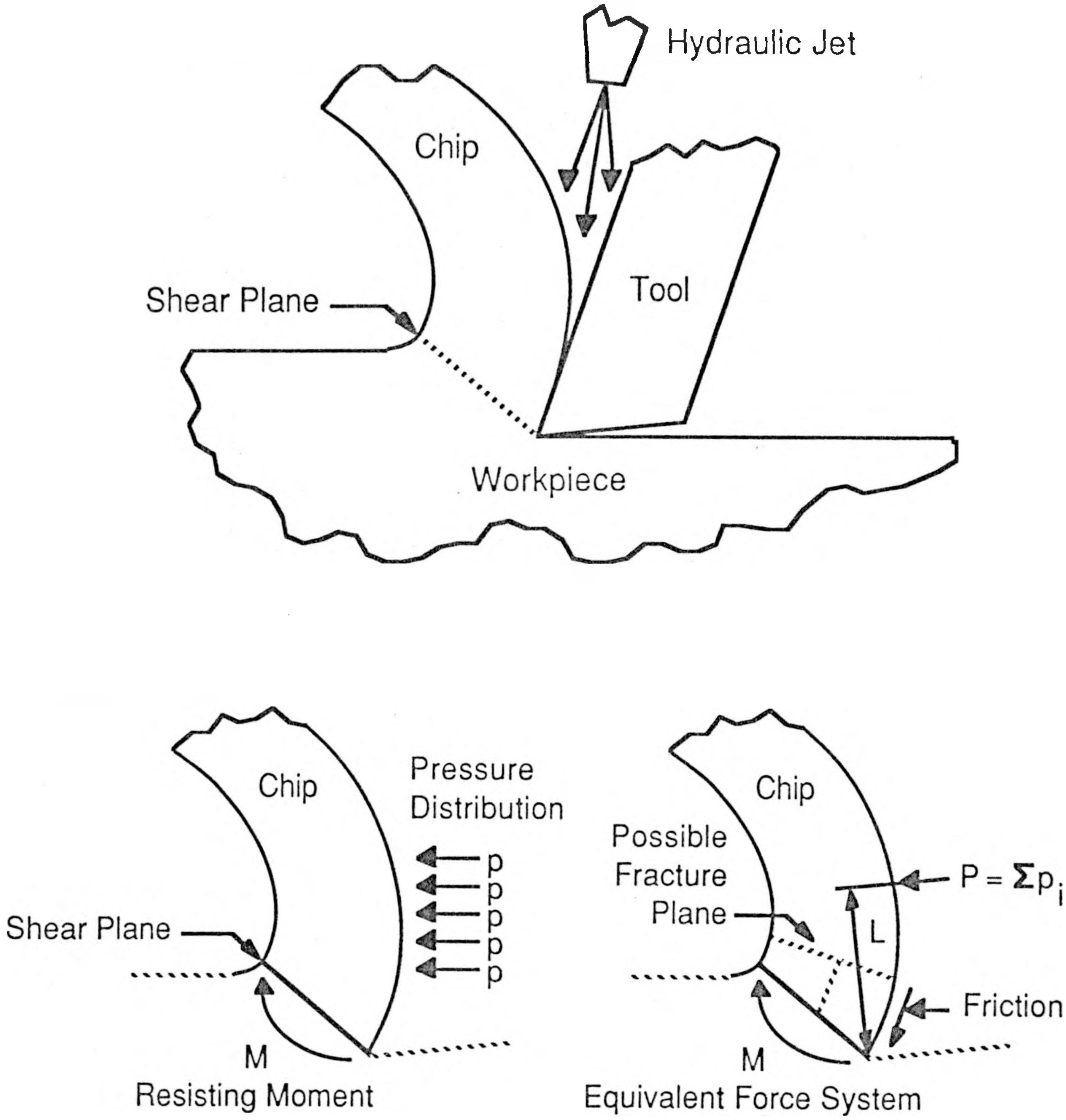

Figure 4. Hydraulic Normal Bending Chip Breaking

normal bending mode system except for the addition of gas bottles, injectors, and control devices. The usual point of injection is near the tool to conserve gas and to better control temperature. About 5% gas is added.

F. Active applied torsion.
No system has been designed or tested using this method. Mechanical means are conceivable and the principle is to use torsion to locally increase the chip formation zone or shear plane stress just as in the systems above. No system of equipment is available. Short helix type broken chips may use the chip weight to exert torsion on the shear zone. In such a case, a flowing stream of coolant may add to the breaking force. Such equipment might use transverse rollers to capture and twist the chip. A mechanical or other drive system would then be needed.

II. <u>Chip Cutting or Formation Interruption Methods</u>

A. Active feed or plunge interruption.
Mechanical systems use cams or hydraulic vibrators to cause a temporary pause or dwell in the cutting. This stoppage then terminates the chip each time motion is halted. Other variants of this method use the numerical control (NC) program to achieve pauses in the action. Pumps and actuators, or cam systems with mechanical or electrical drives would be needed for some systems and NC software changes would be needed for the programmed approach. See references 73-80. Nakayama also suggested precut grooves in the workpiece which would momentarily interrupt the cut (8).

B. Active workpiece indenters.
These use knurling tools or similar rollers to produce indented lines in the workpiece ahead of the tool. The impressions then serve as stress risers to enhance the breaking of the chip and also reduce the chip curl radius. In addition to the limited roller life, the method requires an elaborate system for cuts on parts other than cylinders in order to position the roller at the proper position on the the tool nose radius. Equipment consisting of tool holder systems with added knurling rollers ahead of the tool insert plus perhaps mechanical, electrical, or hydraulic roller positioning systems would be needed. See Figure 5.

C. Cutters and choppers using mechanical systems electric arcs, laser pulses, and abrasive jets have been offered as proposed chip breaking methods. These methods have not resulted in successful practical devices as yet and no such devices are known to be under development.

D. Ultrasonic chip breakers.
Some of these have been conceived to be choppers, but all applications have mainly influenced the chip curl radius through alteration of the chip formation process in the shear

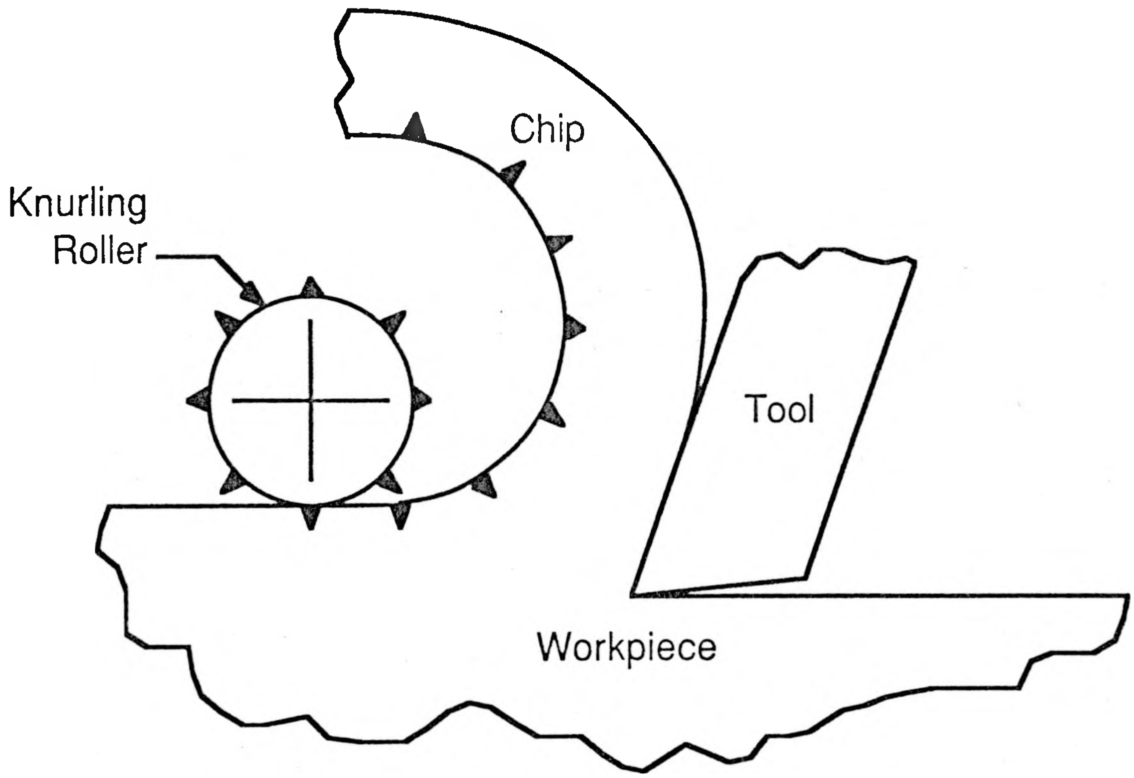

Figure 5. Indenters as Chip Breakers

zone. It could be potentially valuable as a complementary process added to some of the other chip breaking methods. Some ultrasonic transducers have been produced and tested. Additional necessary equipment to position the transducer, an amplifier to excite, and a set of controls are also required. Some work indicates that ultrasonic excitation while improving the cutting also increases the chip curl radius(24)

III. Chip Capture or Entrapment Methods

A. Funnels. These are suggested means for directing the flow path of the chip away from the work zone. For cutting cylinders the funnel may be fixed in its position, but for more complex contours, the funnel would require active positioning of the mouth to capture the chip. Such systems have often been proposed, but none have apparently been developed as a working system for contouring cuts. Nakayama reports success for such a system on cylindrical cuts (8).

B. Diverters. A way to enhance the tendency of chips to form an entangled bird's nest structure but at a location out from the work zone may be called a diverter. Again, this is a proposed system but none has been developed.

C. Reel methods. These are methods to capture and wind up the chip similarly to an automatic motion picture projector or threader to a tape recorder. Some proposed applications of this method, might embed the chip in a soft matrix. No chip handling system like this is known to be developed although the technology is known for other applications. The preferred chip form for all these capture systems would be the straight chip since it would be easier to engage and divert or capture.

EVALUATION OF THE CHIP BREAKING METHODS AND STATUS

I. Chip Fracture Methods

A. Passive mechanical fracture.
A large number of the cutting tool inserts available use this method. A ridge or obstruction is molded into the top of the tool rake face or a groove is cut near the cutting edge. Earlier designs and some tools still used, add a clamped-on ridge or chip breaker. Such clamped breakers are very operator dependent for accurate setting. The greatest number of references in the literature are devoted to issues concerning mechanical breaking. The factors which determine the success in chip breaking are those which make the chip more brittle, increase the section modulus (primarily by increasing thickness), and make cracks or stress concentrations in the chip. Also, the distance of the

obstruction (chip breaker) back of the tool edge along the chip flow path is very critical to chip breaking. The breaker surface must be oriented at an angle which will produce good flexural displacement of the chip. A small curl radius equals a large flexural strain. Most of the papers are concerned with ways to increase the range of cutting conditions over which the passive breaker will produce chip fracture. These breakers are usually sensitive to the depth of cut and the feed rate. Rake angle, cutting speed, friction coefficient, tool nose radius, and strain hardening characteristics of the material also alter the breaking by changing the shear angle and the chip curl radius. Thus, it is not unusual to have a breaker for roughing cuts that will not work for very light finish cuts because the breaker is too far from the cutting edge. Typical distances are from 4-6 times the feed rate. Since the breaking action is sensitive to the distance between the edge and the breaker, regrinding the tool to achieve greater accuracy can nullify the chip breaking.

Some concerns are illustrated in Figure 6. Notice in the figure, that no system seems to break chips in the fine finishing cut region. Almost no data appears in any of the papers for cut depths less than about 0.01 in.(0.25mm) and feeds less than 0.008 in.(0.2mm). In fact, although the plots all resemble the illustration, generally the data taken represents much deeper cuts and heavier feeds. Also, at first, even in the absence of data in the combined low feed and cut depth region, it might appear that reducing the tool nose radius might afford a means of breaking chips in that region. Perhaps that is true, but data is needed to assure reliable breaking. However, as the tool nose radius is reduced, the corner on either a groove or an obstruction must be even smaller, since the breaker must have a setback from the cutting edge in order to function. Those conditions soon require breaker corners of zero radius, so that an unlimited reduction of tool nose radius does not appear to be an obviously workable approach. Note that the nature of the chips formed also changes as either deeper cuts or greater feeds are used. This change in chip form seems to agree well with a geometrical analysis of the tool tip region which will be discussed later. Almost no data appears in the literature for cutting conditions with depths and feeds in the tool tip region, or where the depth of cut is less than the tool nose radius.

When the chip cross section for the uncut chip is analyzed for the shape and flow direction at the centroid as in Figure 7, it becomes obvious that a groove or an obstruction is seldom positioned to intercept the chip normal to the flow direction. The error in orientation appears to be greater as the depth of cut becomes smaller. Although not shown in the Figure, a similar result applies to decreases in the feed in the tool tip region. Therefore, since the chip flow meets the barrier at an angle other than

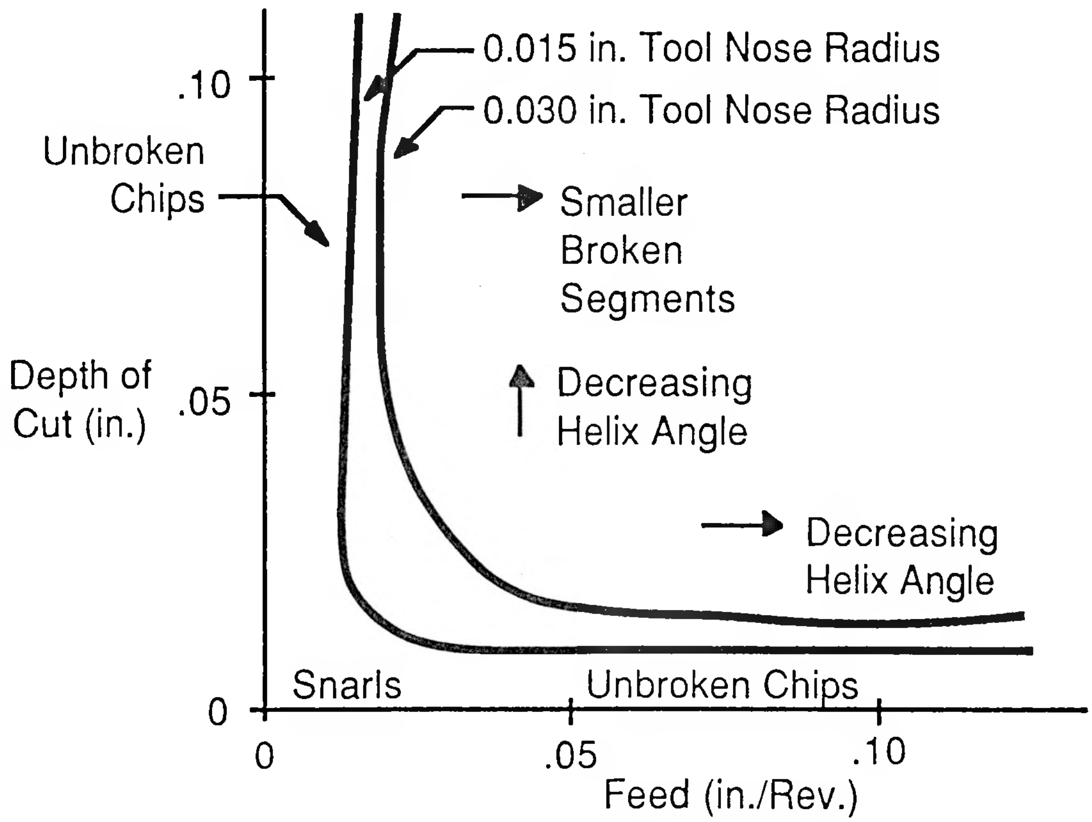

Figure 6. Composite Chip Breaking Chart

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90 degrees, a twisting moment adds to the bending moment acting on the chip in such a way that a helical chip form results. Furthermore, as the depth of cut and feed become smaller, the increased error in the breaker interception angle causes an increasingly large helix angle to the chip form. This agrees well with the observation in a number of papers. To achieve pure bending and ideal one turn or half turn breaking would seem to require an active positioning of the chip breaker so the breaker is always normal to the chip flow direction. This would be an active rather than a passive breaker system. In addition, the orientation problem becomes even greater as the tool nose radius is reduced, since the breaker radius must be even smaller so that small changes in chip flow path make normal barrier interception almost impossible. Failure to approach the barrier normal to it's surface also lowers the effective height of chip displacement and therefore the applied moment to deform the chip. As seen in Figure 8, at least a small amount of data appears to agree with the analysis. Figure 9 also shows the need for data for small depths of cut and small tool nose radii. For tools used to make contouring cuts such as for hemispheres, the cut must use the tool tip region where the depth of cut is less than the tool nose radius in order to maintain a complete contouring cut of uniform depth and preserve the needed contour accuracy.

Wear also alters the distance of the breaker from the cutting edge , and that distance is critical to breaking chips. Wear also limits the degree to which a smaller tool nose radius can be used to achieve better chip breaking. As the nose radius is reduced, wear greatly increases changing the tool edge to breaker distance detrimentally. A further complication in the error in breaker orientation is that for hemispherical cuts, the ideal breaker angle is normal to the chip flow direction and would need to shift as the cut proceeds to move around the tool tip in cutting a hemisphere on an x-z motion machine. Of course, a machine designed to use R-Θ or polar coordinate motion would be able to maintan the same chip breaker orientation to the chip flow throughout the cut.

Generally, when a mechanical chip breaker does not work for some material, the way to produce chip breaking is to increase the depth of cut or the feed rate (4). These techniques increase the chip section modulus and promote good breaking. Such strategies are indicative of practical limits on usable finish cuts if passive breakers are to be used. Another method for increasing the chip thickness or section modulus is to produce small notches in the cutting edge. These are used on drills and end mills. However, the notches cannot be used for accurate turning of hemispheres without loss of accuracy on x-z motion machines.

Some of the critical parameters for the ridge used to

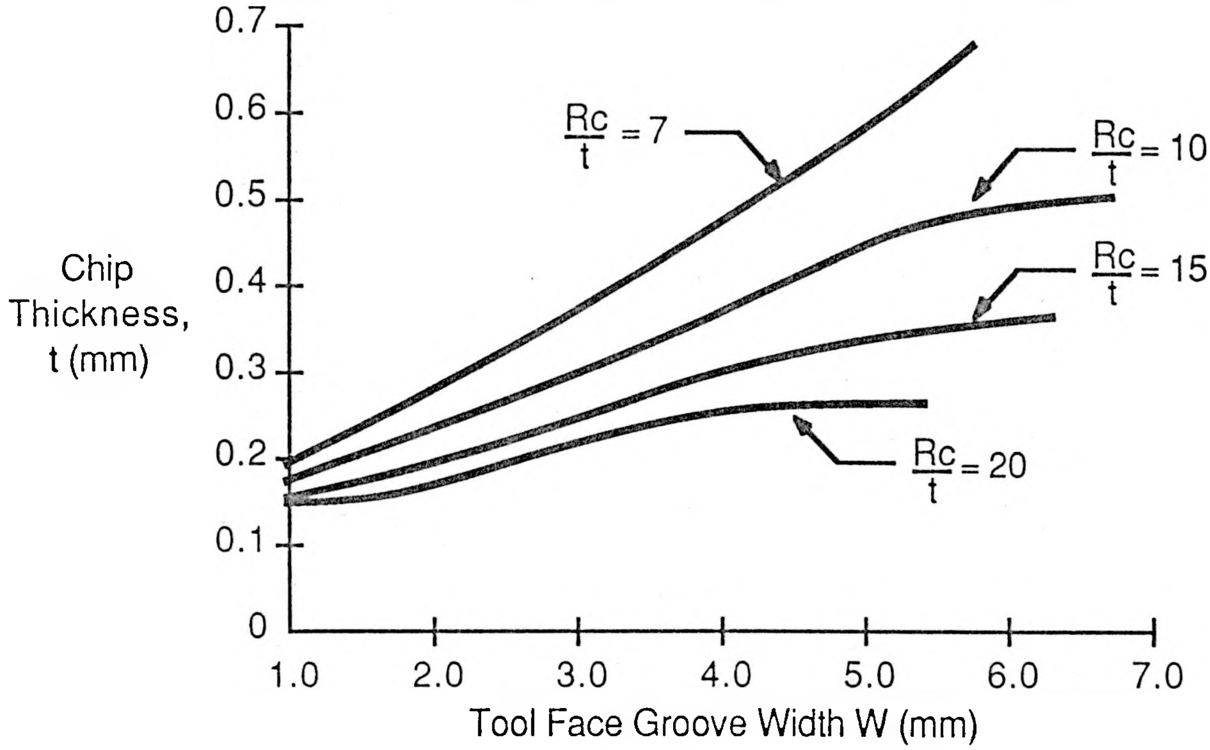

Figure 8. Possible Finish Cut Limits

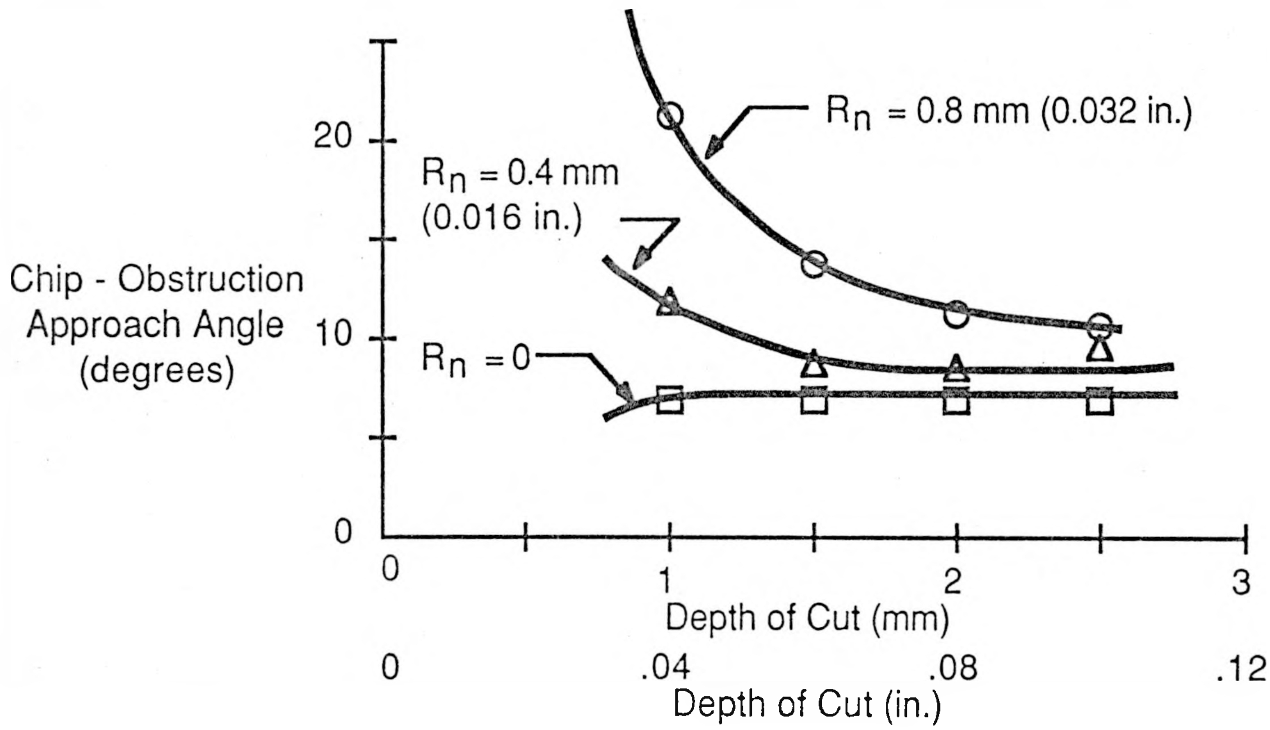

Figure 9. Influence of Tool Nose Radius

break the chips are discussed in references 6 and 10. Most of work reported in the literature concerns depths of cut and feeds much larger than those needed for an automated very accurate turning system. The action of the obstruction lifts the chip and exerts an axial thrust force (6). The lifting not only produces a bending moment but alters the tool friction force which is beneficial in producing the desired chip forms. The thrust force is usually detrimental to good chip form. Thus the desired breaker design would maximize the lifting and minimize the thrust force. A polar coordinate machine control system has advantage in being able to use the passive method and several of the associated chip breaking including notches to locally increase the chip thickness.

B. Active mechanical fracture.
This concept is intended to remove the limitations of the passive system by permitting changes in the breaker location and orientation relative to the tool edge. It has been shown to work well in some limited cases in the literature. However, the active system makes the tool and its mounting more bulky, limiting the proximity to adjacent part features such as steps. A more severe limitation is the fragility of the breaker system for tools with small nose radii. These active breakers are similar to the old clamp-on system, except that a means of moving the position is included. For large tool nose radii, such a system can be made to be fairly robust. But for systems using tools with a nose radius of 0.030 inches or less, the chip breaker would be 0.015 inches or less. Such a small clamped on ridge or breaker may be as likely to be broken by the chip as to break the chip. Thus the active mechanical system would at best need additional development to be useful for fine cuts using small nose radii tools. For the active system as well as the passive system, a finite element model of chip breaking is needed to establish the range of applicable cutting conditions. Some of the devices used for cutting interruption might be modified to accomplish this method.

C. Active hydraulic fracture. Normal bending direction.
Everyone who has ever used a garden hose knows that the energy in a hydraulic stream can be used to perform useful work or to apply a significant force to any object upon which the moving stream impinges. Kennametal engineers have developed and are marketing the equipment necessary to apply this principle to chip breaking in the metal working industry. By applying a force to the lower portion of a forming chip, it can be bent back upon itself in a sufficiently small radius that fracture occurs and the chip falls free. When the stream is directed between the tool rake face, the chip forming conditions are easily attained which fracture the thicker chips of brittle materials. We call this mode of fracture the normal bending mode to distinguish it from at least two other modes in which the hydraulic stream can be used to achieve effective chip removal. These are transverse and orthogonal directions with respect to the forming chip.

These two modes are important because the chip has unique properties and different failure modes in each of its primary directions. These characteristics can be used to advantage in many situations.

The idea of using a hydraulic stream to impart forces upon the chip to cause it to break is significant because of the simplicity of employing it at the tool tip and because of several other advantages that result from the lubrication and cooling which inherently result from use of a high pressure, high flow coolant stream. To date little information has been published on these concepts and no effective modeling methods have yet been proven to work for all situations. To date, applications work has been directed at those operations that generate large volumes of chip material. Only recently has interest been generated in developing the concept for finish machining applications and tougher materials. Complete factory automtion is the need that drives interest in this area. With proper geometric and hydraulic conditions, effective chip breaking has been done on chips formed from finish machining conditions using 0.005 in.(.125mm) depth of cut and 0.005 in.(.125mm) feed per revolution. Figure 10 is a map of the hydraulic regime in which hydraulic chip breaking occurs. Three distinct chip conditions can result during operation and one undesirable part surface condition may form as a consequence of chip breaking. The three conditions are 1) continuous chips, 2) discontinuous or short helix chips, and 3) effectively broken chips. Since the transitions between these chip types do not occur abruptly it helps to define them more specifically. Effectively broken chips are those which are easily removed from the machine by hydraulic flow and generally have chip length to width ratios less than about 15:1. Discontinuous, short chips may still be effectively removed from the machine, but have length to width ratios in the range of 25:1 or greater and are pieces generally shorter than 1 to 2 inches. Because of the extreme energy imparted to the chip at high stream velocities there is the potential to severely damage the newly finished part surface in the region just behind the tool tip. Chip rejection direction is the primary method of control to eliminate this effect when present.

Special concerns exist when employing this method of chip breaking. Some of the problems which it may introduce are: maintaining accurate part temperature control, part spray hooding, mist dispersal, chip transport and control within the machine environment, and the operators noise environment from both the jet and the hydraulic supply pump. Each of these concerns must be addressed in engineering any installation. Although only aqueous cutting solutions have been used to date, it is obvious that other fluids could be used if pumps and collection systems were properly designed. Increased tool life is one of the extra benefits that most users have enjoyed as a result of employing this method of chip breaking. References 70, 71, and 72 address this method.

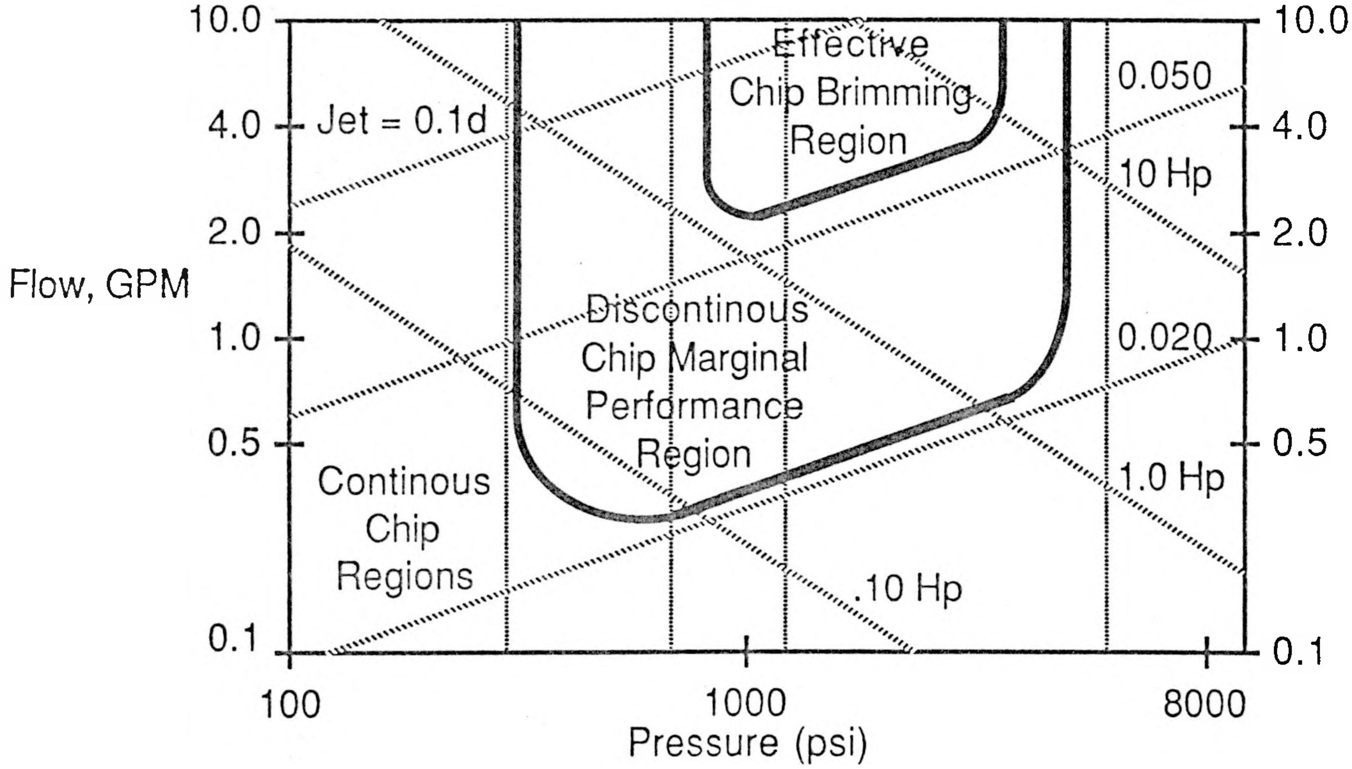

Figure 10. Hydraulic Chip Breaking Map

D. Active Hydraulic Fracture, Orthogonal and transverse directions. As discussed above, the use of hydraulically applied forces can take many forms. Transverse direction chip breaking has been successfully employed in controlling chips produced by super precision diamond turning operations. Both air pressure and vacuum have been used to break and transport these very fine chips. Transverse fracture is particularly attractive in some turning operations.

Orthogonal chip breaking research is just beginning, but it is also apparent that this concept can take advantage of a chip characteristic which other methods cannot utilize. The typical chip is a highly cold worked piece of material which contains a convoluted upper surface containing many deep cracks. These natural stress concentration factors can be used to facilitate chip breaking. Measurements have shown that it takes only between about one fourth to one tenth the force needed to break a chip in the orthogonal direction as compared to the normal direction of bending. Research is continuing on utilizing this concept.

E. Active cryo-hydraulic fracture. Normal bending force. The mechanics of chip breaking using this method is very similar to the hydraulic system described above. The addition of a refrigerant gas may more effectively couple the jet to the chip and should be examined. It is likely to result in superior temperature control in the manufacturing system which is important to maintain the system accuracy. The patent is held by Lodge and Shipley, Ulticon. It should be possible to use the computer model developed for the normal bending mode hydraulic system and add the conditions produced by the refrigerant. Since the material properties are temperature dependent it is not evident what influence there may be on the strain hardening and friction. Physical property changes such as those could change the curl radius and the type of chip breaking as a consequence. Chips formed are the half circle or crescent shape and only lifting of the chip is involved. References discussing the hydraulic system with normal bending apply to these systems too.

F. Active applied torsion. Computer models designed to relate the application of bending stress to the physics of chip breaking would also be useful in testing the usefulness of a torsional load in breaking chips. Since no devices are available and this method has apparently not been used, the model prediction can serve as a screening test. For the time being, inclusion of both torsional and axial loads on the chip and calculation of the influence of each type of loading on the shear angle would be useful as an output of the FEM analysis. No existing references were found for this. Weight may exert torsional loads on short helix chips and coolant flow adds additional components.

II. Chip Cutting or Formation Interruption Methods

A. Cutting interruption

Apparently this method has been fairly extensively used and has been successful judging from the literature. No measurable damage to contours or surface finish has been reported. However, any pause or dwell in the feed of a tool leaves a visible cosmetic burnished or shiny line on the part. These lines are caused by the relative displacement of the tool and the workpiece by the cutting forces acting on the system. Attempts to use this method can make lines which have been known to result in rejection of parts on a visual inspection basis. In addition, the programmed interruption needed to produce short chip lengths would add many times the cutting duration and could be very noisy even at modest surface speeds of 200 to 400 ft per minute. For example, cutting chips to 1 inch lengths at 300 sfm, would require interruptions of 60 cycles per second, and at the displacements to terminate chips, could be very noisy and require large amounts of power. Clearly, to avoid that consequence would probably require accepting fairly long segments of chip. Long segments of chips were considered in the estimates given by Russian authors (75) who both slowed the cutting and allowed for one chip per revolution to achieve a one Hertz frequency. However, one chip per revolution would produce 24 inch long segments when cutting an 8 inch diameter hemisphere. Such long chip segments would hinder automation almost as much as unbroken chips. Even 1 inch long chips are somewhat difficult to handle in automatic operation and are much longer than the segments from the hydraulic method. Although some early work on this method was done in the United States, most of the more recent work has been done in Russia and Britain. This method works independently of the form of chip being generated, the material properties, the friction, the depth of cut, and the feed rate since chip length is determined by the selection of the frequency of interruptions.(73-80)

A variant of this method mentioned by Nakayama (8) is to precut a groove in the workpiece which then makes momentary interruptions to the cut. Although not having such a severe time penalty in the cutting process, the major problem is residual remains of the grooving on the finished workpiece caused by reduction of the cutting forces at the groove locations. Although the actual ridges left behind may be within the contour and surface finish requirements, parts are likely to fail to be visually acceptable.

B. Active workpiece indenters.

Several papers in the literature report using knurling tools or indenters to embed lines in the workpiece for fracture enhancement. Most of the papers are Russian. The concept is interesting, but limitation on workpiece geometries usable and tool holder complexity reduce the interest in this method unless all of the others fail. It might be of value to model the placing of external loads at or near the shear plane just ahead of the tool by the FEM analysis. This would simulate one aspect of an indenter and test for any interaction with the shear zone and shear angle. The indenter may reduce the chip curl radius as well and increase the likelihood of breaking by contact. The compressive indentation would be less effective as a stress concentration than the cracking of the outer chip surface produced in normal chip forming as in reference 9.

C. Other cutters and choppers.
The remaining cutter and chopper techniques all suffer from the same limitations as the feed interruption way of breaking chips. That is, either extreme noise and power consumption must be tolerated, or excessive time in cutting and long chip segments must be accepted. Any serious consideration of these methods should await the known failure of the other methods, and then only be used if some viable solution to the presently perceived problems with them is advanced. Of course, ultrasonics could be used to assist other chip breaking methods, but it should be noted that research using ultrasonics to date has resulted in larger chip curl radii under ultrasonic excitation, which is opposite to the desired result.

III. Chip Capture and Entrapment Devices

The entrapment and capture devices are proposed often but no practical devices have been produced. Engaging end of a new chip from tool tip directions varying by more than 90 degrees and producing a reliable device small enough to fit an inside contour restricts the use. Nakayama illustrated a channel in the side of a boring bar tool system, and reported that such a system had been used in camera and small equipment cutting processes. The illustrated device would be limited to cutting cylinders. These devices, as well as the choppers and interrupters have the advantage of working independently of the type of chip that would normally be formed. In fact they would work best with straight chips typical of those produced in cuts using small feeds and depths of cut.

CHIP BREAKING SUMMARY

The most universally applicable systems available at present are the active hydraulic system and the active cryo-hydraulic system applying pressure to break chips in a direction normal to the tool face. These systems are quite expensive, costing from $20,000 to $80,000 but perhaps serving 8 or 9 active tools with one pumping unit when making the very fine finish cuts. Conversely, perhaps units designed solely for finish cuts would be much less expensive. A system shared by several machines could compromise some of the advantages of automation. Mechanically induced fracture of chips in bending is more limited in conditions of application. Presently, the method works well for deep cuts, large feeds, cylindrical cuts, and one design works for a limited selection of metals. Ways to increase the range of applicability is a very fruitful and needed area of study. At present, this method is difficult to apply to chip breaking for very fine feeds and depths of cut when cutting metals that are very ductile. Changes in edge position through wear or regrinding for accuracy also require study to determine the extent to which they may limit operation of an automated system using this mode of chip breaking. This is the least expensive method of breaking chips. Some forms of active mechanical fracture should be further evaluated as means to increase the range of applicability of the passive systems. For machines using polar coordinate control systems this type of chip control works well for contouring cuts and has the added benefit that back and side rake angles can be used. Even though chips break by the commonly observed contact with the tool or the workpiece, other breaking mechanisms may be possible and need investigation. Particularly, the interaction of various types of externally applied chip loads with the shear zone itself should be studied and conditions leading to fracture at or near the shear zone should be studied. Furthermore, data showing any limits tothe usable tool nose radius and cutting edge notches needs to be obtained.

Cut interruption through the tool path or feed changes programmed into NC part programs is fairly inexpensive in terms of equipment but very costly in terms of part production times. Mechanical and hydraulic interrupters sometimes use much the same equipment as the jet systems and while the cost may not be as high, it is probably comparable. There is almost no limit to the range of application, but at the penalty of time and maybe noise. The changes in the surface finish and contour accuracy on contours such as spheres may also eliminate interest in this method.

Other methods, while possibly of value, are not presently developed sufficiently to make realistic application likely in the next few years. They should be examined for feasible means of implementation, and seriously pursued if the other methods fail. Some of these methods may also be useful in a complementary role with the more developed methods.

The summary of the evaluation of the applicability of all of the chip breaking systems to accurate automated turning systems is shown in TABLE I. The score given at the bottom of the table represents a simple unweighted sum of those for each topic listed. Depending on the intended use, a weighting may be useful.

TABLE II shows a composite scoring of the methods most useful for two types of machine tool system and for a variety of materials. Several experienced producers of turned components responded to an inquiry and a composite scoring was determined. The scoring on both Tables is subjective and is intended primarily as a beginning point from which to develop your own scoring. At the present time, the mechanical fracture systems, the hydraulic systems, and the cut interruption methods appear to be the most logical beginning points from which to solve chip breaking and chip handling problems.

CONCERNS REQUIRING STUDY AND TESTING

The following need testing and analysis for use with a very accurate automated turning system using the best present methods of chip breaking:

- Applicable to all materials of interest
- Complete and accurate computer model
- Range of useful geometrical and cutting conditions
- Acceptable time and monetary impact
- Contribute to system accuracy capability
- Capable of integration in an automated turning system
- Able to use a range of coolants in the wet systems
- Acceptable impact on the shop environment
- Compatible with all parts of an automated system
- Capable of automatic control including sensors
- Acceptable system reliability

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TABLE I. COMPARISON OF CHIP BREAKING METHODS

	A	B	C	D	E	F	G	H	I
Unlimited Range	2	4	8	1	8	9	2	7	2
Temp. Control	2	2	7	6	8	1	1	1	1
Contour Accuracy	6	8	7	7	8	6	4	4	4
Surface Finish	6	7	8	8	8	4	3	5	5
Tool Change Time	7	5	4	4	5	7	3	4	3
Cutting Time	7	6	9	8	9	0	3	4	4
Ductile Mat'l	3	5	8	8	8	9	0	9	9
Brittle Mat'l	6	6	8	9	8	8	1	5	0
Hazard Mat'l	7	8	3	3	3	9	1	4	4
Pure Mat'l	8	8	5	5	5	9	3	5	5
Mature Technol	5	3	8	7	8	3	3	0	0
Analyt Support	5	3	7	5	6	3	1	0	0
Noise	6	6	4	5	4	2	1	1	7
Cost per Active Tool	9	7	1	2	0	8	3	3	2
Total Cost	8	6	2	4	1	8	7	6	5
Score	87	84	89	82	89	86	36	58	51

Evaluation based on 10 being best, and is estimated from the present State of the art. Additional study will improve the estimate. Note: In the two cost lines, a low score means a high cost.

A = Passive mech fracture B = Active mech fracture C = Hydro. norm
D = Hydro transverse E = Cryo-hydro norm F = Cut interrupt
G = Indenters H = Choppers (all types) I = Capture systems

TABLE II. CHIP BREAKER-MACHINE TOOL-MATERIAL MATRIX

	A	B	C	D	E	F	G	H
Cartesian or x-z motion machines	6	1	9	7	7	6	1	1
Polar or R-Θ motion machines	9	4	8	8	7	5	1	1
Ferrous low carbon	7	1	8	7	4	6	1	1
Ferrous Stainless 304	7	2	9	7	6	5	1	1
Ferrous Tool steel	7	1	9	8	7	6	2	0
Aircraft Steels	7	1	9	8	7	6	2	0
Titanium	7	1	10	5	9	4	1	1
Beryllium	9	1	1	1	1	0	3	0
High Purity Materials	3	1	4	3	2	8	4	0

Rated on 0 to 10 scale, 10 being the most applicable method.

A = Passive Mechanical Fracture, B = Active Mechanical Fracture
C = Hydraulic Normal Bend D = Hydraulic Transverse Bend
E = Cryo-hydro Normal Bend F = Cut Interrupters
G = Chip Capture H = Torsional Fracture

Scores shown are the composite or average of the 4 ratings from the PFMS chip breaking committee and are as of 4/22/88.

Note: The transverse bending fracture mode includes hydraulic, pneumatic, and vacuum devices to provide transverse loading in addition to gravity.

PASSIVE MECHANICAL CHIP BREAKING SYSTEMS

1. An Orthogonal Metal Cutting Model Based on an Eulerian Finite Element Method, Strenkowski, J.S.; Carroll, J.T. III, Manufacturing Processes, Machines, and Systems, Proc. 13th NSF Conf on Prodctn Res and Technol, 1986

2. New Range of Clamped Tip Lathe Tools, Muzykant, Y.A., Soviet Engrng Res., 6, (3), 1986 (English)

3. Computer Prediction of the Mechanical Outputs of Three Dimensional Turning and Drilling, Stephenson, D.A., Ph.D. Dissertation, Univ. of Wisconsin, Madison, 1985

4. Calculation of Optimum Cutting Conditions for Turning Operations, Hinduja, S.; Petty, D.J.; Tester, M.; Barrow, G., Proc. Instn Mech Engrs, 199,(B2), 1985

5. A Finite Element Model of Orthogonal Metal Cutting, Strenkowski, J.S.; Carroll, J.T.III.,Trans ASME,J Engr for Ind., 107, 1985

6. Some Observations on Machining Steel Using Tools with Step Type Chip Breakers, Radwan, A.K.A.; Taher, R.M. Proc. 12th NAMRC, Soc. Mfg. Engrs. 1984

7. Experimental Research of the Chip Flow Direction and its Application to Chip Control, Jiang, C.Y.; Zhang, Y.Z.; Chi, Z.J., Annals of CIRP,34, 1984

8. Chip Control in Metal Cutting, Nakayama, A., Bul. Japan Soc. Prec. Engrng. 18, #2, 1984

9. Fracture on the Shear Plane in Continuous Cutting, Sampath, W.S.; Shaw, M.C., Proc 11th NAMRC, Soc Mfg Engrs, 1983

10. Chip Control in Turning, Nakamura, S.; Christopher, J.D., Wuebbling, G.J.,Proc 11th NAMRC, Soc. Mfg. Engrs., 1983

11. Influence of Friction on the Shear Angle in Machining, Wright, P.C.; Bagchi, A.; Chow, J.G., Proc 10th NAMRC, Soc Mfg Engrs, 1982

12. Advent of High Performance Groove Geometries, Hazra, J. Australian Machinery & Prodctn Engrng, 35, (4), 1982

13. Trends in Cutting Tool Inserts, Miller, P.C.; Arbuckle H.J., Tooling and Production, Feb. 1981

14. Productivity in the Groove, American Machinist. 125, (7), 1981

15. Cutting with a Curved Rake Face, A Means for Breaking Thin Chips, Nakayama, K.; Arai, M.; Kondo, T., Annals of CIRP, 30, (1), 1981

16. The Physical Model of Continuous Chip Formation in Machining, Kufarev, G.I., Soviet Engrng Research (English), 1, (10), 1981

17. Effect of Chip Breaking Inserts on Minor Cutting Edge Chipping, Litagawa, R.; Kahng, C.H., ASME Paper # 81 WA/Prod 11, 1981

18. The Selection of Suitable Chip Breaking Shapes for Throw Away Cutting Tips, Schubert, H.D., Werkstatt. Betr. 113, (5), 1981 (German)

19. Chip Grooves Take on High performance Role, Hazra, J., Machine and Tool Blue Book, 75,12, 1980

20. Designed in Chip Control, Weller, E.J., Tooling and Production, 45,(11), 1980

21. Chip Curl, Chip Breaking, and Chip Control of the Difficult to cut Materials, Chang, Y.Z., Annals of CIRP, 29, (1), 1980

22. The Effect on Cutting Tool Wear of Various Types of Chip Control Device, Redford, A.H., Annals of CIRP, 29, (1), 1980

23. Cutting Tools Spark Productivity, Williams, V.A., Production, 85, (4), 1980

24. Ultrasonically Assisted Machining of Aircraft Parts, Devine, J.; Krause, P.C., Report # TR 80 F 18, Final Report, Contract # DAAG 46 78 C 0059, U.S. Army Research and Development Command, 1980

25. The Breakability of Chip in Metal Cutting, Nakayama, A.; Arai, M., Proc. Int'l Conf on Mfg Engrng, Melbourne, Aus. Aug 1980

26. On the Mechanism of Chip Breaking, Kaldor, S.; Ber, A.; Lenz, E., Trans ASME, J. Engrng for Ind. 101,(3), 1979.

27. New Concepts in Chip breaker Design Leads to a Wider Range of Chip breaking, Ber, A.; Kaldor, S.; Lenz, E., Soc. Mfg. Engrs. Paper # MR79 307, 1979

28. Predicting Breaking with Groove Type Breakers. Worthington, B.; Rahman, M.H., Int. J. Mach Tool Design and Research, 19, (3), 1979

29. The Effect of the Chip Breaker Constraints on the Mechanics of the Machining Process, Dewshurst, P., Annals of CIRP, 28, (1), 1979

30. Present Knowledge of Chip Control, Kluft, W.; Konig, W. VanLuttervelt, C.A., Annals of CIRP,28,(2), 1979

31. Optimizing Performance of the Cutting Edge, Lundgren, E New Frontiers on Tool Materials, Cutting Techniques, Metal Forming, Session II, Paper 1, London, Mar. 1979

32. Chip Breaking when Turning Large Parts, Mansyrev, I.G.; Limarev, V.P., Machines & Tooling, 50,(8), 1979 (English)

33. Analysis of Swarf Breaking Devices, Lavrov, N.K., Russian Engrng J.(English), 57, (10), 1979

34. Determination of Forces in Cutting with a Tool Having a Chip Breaker, Faslavskii, I.Y.; Bezrukov, O.Y.,Izv. V.U.Z. Machinostroenie (11), 1979 (Russian)

35. Effects of Steel Chemistry on Chip Formation in Metal Cutting, Watson, J.D.; Brown, G.G., 4th Tewksbury Conf on Fracture, Melbourne, Australia, Feb 1979, Univ of Melbourne.

36. New Chipbreaker Range of Applications, Decreases Stock Requirements, Gertler, S., Cutting Tool Engrng, 29, (5,6,7,& 8), May-Aug 1977.

37. Tool Failure and Chip Form as Restrictions when Selecting Data, Rasch, F.O.: Tonnessen, K., Annals of CIRP, 26,(1), 1977

38 Design of Molded in Chip Breaker in Throwaway Inserts, ElGomayel, J.; Pinto, J.C., New Developments in Tool Materials and Applications. Ill. Inst. of Tech. Res. Inst., Mar. 1977

39. Study on Chip Excluding. Effects of Cutting Tool Shapes and Cutting Conditions on the Chip Excluding, Minato, K.; Teshima, T., J. Japan Soc Precis Engr,43,(6), 1977

40. Devices for Producing Short Chips in Turning, Muller Gerbes, H.; Hohmann, H., Ind Anz., 99, (51) 1977 (German)

41. On the Storage of Data on Metal Cutting Forces, Nakayama, K.; Arai, M., Annals of CIRP, 25,(1), 1976

42. The Operation and Performance of a Groove type Chip Forming Device, Worthington, B.. Intl J of Prodctn Res., 14, (5), 1976

43. Cemented Carbide Cutting Tool Materials, Shaw, M.C. Carbide Journal, 7,(3), 1975

44. Effect of Chip Forming Devices on Tool Wear in Metal Cutting, Boothroyd, G.; Reinhart, L.E., NAMRC Conf. Soc Mfg. Engrs. 1973

45. Chip Curl and the Action of the Groove Type Chip Former Worthington, B.; Redford, A.H., Int. J. Mach Tool Design and Research, 13,(4), 1973

46. Importance of Efficient Chip Breaking, a Paper Dealing with Indexable Inserts having Sintered Chipbreakers, Canadian Machinery and Metalworking, 84,(4), 1973

47. Chip Control, Design Innovations which Increase the Chip Control Range and Capacity of Indexable Inserts, Sperandio, B., Soc. Mfg. Engrs. Paper MR73-904, 1973

48. A Study of Preformed Chip Control Devices in Throwaway Carbide Inserts, Jones, D.G.; McCreery, J.F., Soc. Mfg. Engrs. Paper MR73-215, 1973

49. Chipbreakers, Lundgren, E., Canadian Mach Metalwork, 84. (4), 1973

50. Breakability, An Aspect of the Machinability: A Computer Simulation of Chip Formation, Spaans, I.C.; Goedemondt, A.A., Mfg. Engrng. Trans. 1, 1972

51. Some Investigation on Chip Curl on Chip Breaker, Kaul, R.L.; Singh, C.K., Proc. 5th All India Machine Tool Design and Research Conf. Univ of Roorkee, 1972

52. A Systematic Approach to Three dimensional Chip Curl, Chip Breaking, and Chip Control, Spaans, I.C., Mfg. Engrng. Trans., 1, 1972

53. Effect of Wear on Chip breaker grooved Tools, Nodel'man M.O., Russian Engrng J. (English),LII, (8), 1972

54. The Effect of Tool Geometry on Chip Breaking, Kane, G.E. 1st Intl Cemented Carbide Conf., Soc Mfg. Engrs., Vol.II Paper MR71-923, 1971

55. Break Mechanisms in Cutting with a Chipbreaker, Spaans C.; VanGeel, P.F.H.J., Annals of CIRP, XVIII,(1), 1970

56. Chip Breaker for Finish turning, Savilov, A.D., Machines & Tooling, 41,(5), 1970 (English)

57. Chip Breaking by Rolling Tool, Shinozaki, N.; Hirota, H. Soc. Mfg. Engrs. Paper MR70-250, 1970

58. Tooling Up for Stainless, Clarke, W.C. Jr., American Machinist, 113,(12), 1969

59. Action of the Obstruction Type Chip Former, Trim, A.R.; Boothroyd, G., Intl J. of Prodctn Res., 6,(3), 1968

60. Research on Swarf Removal Systems, Schomburgk, I.C., Machinery and Prodctn Engrng, 111,(2857), 1967

61. A New Explanation of the Phenomenon of Chip Curling During Machining, Ponkshe, G.R., Trans ASME, J. Engrng for Ind. May 1967

62. Tools with Chip curling Grooves, Igoshin, V.V., Machines & Tooling, 36,(12), 1965 (English)

63. Chip Breakers, Hummer, J.; Goeppert, A.P., Machine and Tool Blue Book, Nov. 196 1980

64. Chip breaking Methods in Turning Ductile Materials, Baranov, V.N.; Zakharov, Y.E.; Moiseev, V.E.; Bezrukov, I.M., Machines & Tooling, 34, (1), 1963 (English)

ACTIVE MECHANICAL CHIP BREAKING

65. Chip Breaker Considering Chip Flow Direction, Oh-uchi, K.; Asano, K., Research & Development, 36, (4), 1986

66. Kinematic Chip Breaking Methods in Metalcutting, Mansyrev, I.G., Machines & Tooling, 47,(2), 1976 (English)

67. Special Purpose NC System (with Operational Memory for Optimal Control and Kinematic Chip Breaking), Gornev, V.F.; Savinov, A.M., Machines & Tooling, 45, (12), 1974 (English)

ACTIVE HYDRAULIC CHIP BREAKING. NORMAL BENDING.

68. Chip Breaking System for Automated Machine Tool, Arehart, T.A.; Carey, D.O., Patent No. US 4,643,056., Martin-Marietta Y12 Plant, Oak Ridge, TN. Feb 1987

69. Chip Breaking on Uranium Alloy, Morris, T.O.; Tharp, M.J., Martin-Marietta Y12 Plant Report # Y 2389, Oak Ridge, Tn. Sept 1987, Nat'l Tech Info Service

70. Method and Apparatus for Machining, Yankoff, G.K., Patent No. US 4,621,547, Assigned to Kennametal. Nov. 1986

71. Hydraulic Chipbreaking, Rasch, F.O., Annals of CIRP, 30, (1), 1981

72. Some Effects of Injecting Cutting Fluids Directly into the Chip Tool Interface, Sharma, C.S.; Rice, W.B.; Salmon, R., J. Engrng for Ind, p441-444, 1971

MECHANICAL INTERRUPTION OF CUTTING

73. Vibration Assisted Metal Turning, Medeksza, L.A., Proc 3rd Cairo Univ MDP Conf, Cairo, Egypt, Dec. 1985 Pergamon Press

74. The Effect of Cutting Speed on the Dynamics of Vibroturning, Kamalov, V.S.; Kugultinov, S.N., Russian Engrng J., 59, (10), 1979

75. Kinematic Chip Breaking Methods in Metal Cutting, Mansyrev, I.G., Machines & Tooling, 47,(2), 1976 (English)

76. Special Purpose NC System, Gornev, V.F.; Savinov, A.M., Machines & Tooling, 45, (12), 1974 (English)

77. Vibratory turning Attachments for Universal Centre Lathes, Molochko, V.I., Machines & Tooling, 44, (4), 1973 (English)

78. Hydromechanical Vibrating Swarf breaking Device, Sitnikov, B.T., Machines & Tooling, 43,(5), 1972 (English)

79. Chip Breaking in Finish Turning of Varying Feed, with High Surface Quality Maintained During Entire Tool Life Spaans, C.; Hovinga, H.J., Proc 1st Intl Cemented Carbides Conf, Soc of Mfg Engrs, Paper MR71-904, 1971

80. Chip Breaking by Induced Tool Vibration, Dohmen, H.G., Ind Anzieger, 88, (59), 1966

MECHANICAL WORKPIECE INDENTERS

81. The Force due to the Action of a Knurling Roller Tooth in Turning with Leading edge Plastic Deformation and Chip Crushing, Yaroslavtsev, V.M.; Sabel'nikov, V.V., Izv. V.U.Z. Mashinostroenie, (6), p 133-136, June 1981 (English)

82. Life of Knurling Rollers Used for Chip Breaking in Turning Operations, Yaroslavtsev, V.M.; Talaev, A.N., Machines & Tooling, 47, (3), 1976 (English)

GENERAL MACHINING LITERATURE

83. The Manufacturing Engineers Handbook, Vol. 1, Machining, 4th Ed., Soc Mfg Engrs, 1983