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A Knowledge-Based Approach for Designing Effective Grooved Chip Breakers – 2D and 3D Chip Flow, Chip Curl and Chip Breaking

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This paper presents details of a knowledge-based approach for designing effective grooved chip breakers for two- and three-dimensional chip flow, curl and breaking. The design criterion used in formulating this new approach is effective chip breaking at minimum power consumption. This work was aimed at achieving the optimum groove parameters and the best utilisation of groove profile under varying machining conditions. A systematic knowledge-pool was established from a series of well-designed machining experiments which form four knowledge databases (reference database, grooved chip breaker database, natural contact length database and 3D chip flow database). This paper shows how the chip breaker design parameters can be estimated for effective chip breaking at reduced power consumption. The basic tool design strategy presented in the paper also includes some guidelines, for cutting tool designers, highlighting the need for implementing a scientific approach for designing a chip breaker against the current practice of "try and see" methods.

Keywords: Chip breaker; 2D and 3D Chip flow; Knowledge-base; Machining; Tool design

1. Introduction

It has long been known that chip control in metal machining, particularly in continuous mode operations such as turning, is vital owing to its significant role in producing small and handleable sized chips for disposal, and in protecting the machined work surface, cutting tool, machine tool and operator (in manual operation) from long, snarled, hard and hot unbroken chips. With the advent of automated manufacturing technologies involving unattended machining operations, the need for chip control has grown.

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Recent advances in cutting tool technology have resulted in a great number of different chip breaker configurations. However, the current practice in chip-groove design and application is heavily dependent upon extensive, arbitrary and non-systematic experimental work, which is primarily based on the "try and see" methodology. This practice is time-consuming and does not always produce the most desirable chip breakability concerning optimum chip groove utilisation and the associated minimum power consumption. Therefore, a more scientific and effective approach for designing tool chip breakers is needed to replace conventional methods. The need for developing a knowledge base from a database system has been shown to be essential both for designing effective chip breakers and for achieving "total" chip control in automated machining [1, 2].

The tool restricted contact and chip-groove configurations have been identified as the most important parameters for designing effective grooved chip breakers [3]. Such an effect makes the chip flow back into the cavity on the tool rake face in order to allow the chip to curl effectively for subsequent breaking. In the present work, four grooved chip breaker styles (groove profiles with raised backwall, standard backwall, reduced backwall and no backwall) with varying sizes (GT1, GT2 and GT3) and restricted contact lengths (h) were selected to develop a systematic knowledge database. Once such a database has been established, a quantitative description of the effects of various tool parameters and process variables on chip breaking performance can readily be achieved. The new methodology presented in this paper for designing grooved chip breakers provides a basic and comprehensive model for achieving the design parameters of a more effective and complex tool chip breaker.

2. Chip Control with Grooved Chip Breakers – General Background

An authoritative survey on chip control was conducted under the sponsorship of CIRP (International Institution for

Production Engineering Research) [4]. Almost a decade later, a major survey on chip control was undertaken by Jawahir [1]. This survey was followed by a review of current status in chip breaking [5]. Most recent initiatives of CIRP include activities of a three year working group on chip control which concluded its activities with a 1993 CIRP keynote paper [2] and an extensive computerised literature database on chip control to date [6].

State-of-the-art reviews presented in all these works confirm that innovative chip breaker designs dominated the developments in the 1980s. Also, it has been found that the basic mechanism of chip flow in the majority of chip breakers can be explained as resulting from the combined effect of both the tool restricted contact and the tool face configuration, which is, in most cases, a groove or a cavity of varying size and shape.

2.1 Tool Restricted Contact Effect as a Major Factor in Chip Breaking

Johnson [7] presented the first model of cutting with restricted contact tools as a centred fan slip-line field and a corresponding hodograph. Usui et al. [8, 9] subsequently verified this model, both, theoretically and experimentally. A key aspect which resulted from these analyses, apparently without much attention being paid to it at that time, was the effect of chip backflow. This was later found to play a significant role in chip curl and the subsequent chip breaking process when machining with grooved chip breakers having a tool restricted contact adjacent to the groove profile [3]. Experiments with tools having various tool contact lengths have shown that there exist the following three general relationships [10]:

$\eta_b < \alpha$, when $h > h_n$
(chip curls upwards before reaching the chip-groove)
$\eta_b = \alpha$, when $h = h_n$
(chip flows straight, with no curvature) (1)
$\eta_b > \alpha$, when $h < h_n$
(chip enters the chip-groove as a result of chip backflow)

where h is the tool restricted contact length, h_n is the tool/chip natural contact length, α is the tool rake angle and η_b is the chip-backflow angle.

2.2 Chip Curl Mechanisms with Grooved Chip Breakers

It is believed that industrial applications of grooved carbide tools began in the 1950s with significant developments in cutting tool design following Henriksen's early works on chip breakers [11, 12]. In 1956, Fine [13, 14] contributed to the development of grooved chip breakers with his excellent work on conventional and unconventional chip-grooves. Soviet researchers, notably Lutov [15] and Sisoev [16], produced designs for various chip-grooves and presented a method for optimum groove size selection. Worthington investigated the effect of rake face configurations on chip curvature [17]. In a subsequent work, he presented a more detailed analysis of the operational performance of grooved chip breakers [18]. In this work, the critical value of feed beyond which the chip breaker groove becomes effective (owing to the chip backflow into the groove) has also been shown. In 1979, Worthington and Rahman [19] presented an analysis for predicting chip breaking under oblique conditions.

Works by Ber et al. [20] and Kaldor *et al.* [21] were based on several innovative chip-groove geometries and show how to improve chip breakability over a wider application range. Nakayama et al. [22] introduced various new chip groove geometries for breaking thin chips. Oxley [23], in his work on the mechanics of machining, has shown the need for predicting the tool/chip natural contact length from his well-established predictive theory. Jawahir and Oxley [24], by showing experimentally the effect of chip backflow in conjunction with various tool chip-groove profiles, have identified the corresponding variations in chip curvature and hence chip breaking.

2.3 Power Consumption with Grooved Chip Breakers

Sisoev in his early work in 1962 "touched on" the power consumption rates when machining with grooved tools [16]. Spaans in his extensive work on chip breaking indicated the possibility of power reduction with grooved chip breakers by altering the tool geometry and cutting conditions [25]. Bator, by a high-speed filming technique [26], compared the power consumed when using a "land-angle" tool and conventional grooved chip breakers. His work has shown that properly designed land-angle tools will provide lower power consumption. Ber et al. [20] and Kaldor et al. [21] also provided several new tool geometries which reduced power consumption in machining.

In a more recent work, Jawahir and Oxley [24] have reported the possibility of achieving efficient chip control at reduced power consumption. In this experimental work three different chip-groove sizes and four different chip-groove styles were used with varying tool restricted contact lengths under a wide range of cutting conditions.

2.4 3D Chip Flow, Curl and Breaking with Grooved Chip Breakers

In oblique machining with 3D chip flow, the effects of these two factors will be combined with the effects of tool nose radius and chip-sideflow angle to determine the chip breaking performance and power consumption.

Many researchers have presented various cutting models for predicting chip flow in machining [25, 27–32]. All these investigations were based on the use of flat-faced cutting tools. However, the chip flow in practical oblique machining with grooved tools having varying tool geometries, is far more complex than that for the flat-faced tools. Furthermore, the chip flow when machining with grooved tools having various toolface configurations is even more complex. When dealing with a grooved chip breaker with varying tool restricted contact lengths, the effect of 3D chip flow can be presented by two components, chip-sideflow angle η_s and chip-backflow angle η_b. As shown in Fig. 1, η_s is the angle formed by the chip sideflow on the toolface projected onto the (X,Y)-plane and η_b is the angle formed by the chip downflow (i.e. streaming towards the groove) projected onto the (X,Z)-plane. An extensive work on machining with tools having conventional grooves involving combined chip sideflow and backflow has recently been reported [33].

2.5 General Comments on the Present Knowledge of Chip Breaking with Grooved Chip Breakers

It has been noted that the effect of tool restricted contact on chip backflow has not been fully understood until recent times and hence most researchers assumed that the chip fully utilises the groove profile, quite independently of the groove dimensions and the tool restricted contact on the toolface. There was very little work done on means of achieving efficient chip control at reduced power consumption, whilst the major emphasis was centred on improving chip breakability by introducing different chip groove geometries which quite often proved to be more power consuming.

The development of new, more efficient methodologies such as AI applications for chip control has been used in the most recent state-of-the-art review of chip control [2]. Also, the need for designing chip breakers for improved performance, both in terms of reduced power consumption and enhanced chip breakability, has been at the centre of developmental activities in the cutting tool industry. The basic aim of the present work is to present a knowledge-based approach for chip-groove design. The motivation for this work is the observation of current practice of chip-groove design which is in effect time-consuming and unscientific. A vast amount of "knowledge" on chip breaking exists, but it is scattered and not fully utilised in tool insert design. A "user friendly" methodology is presented in this paper for choosing the best chip-groove parameters for a given set of cutting conditions and tool geometry.

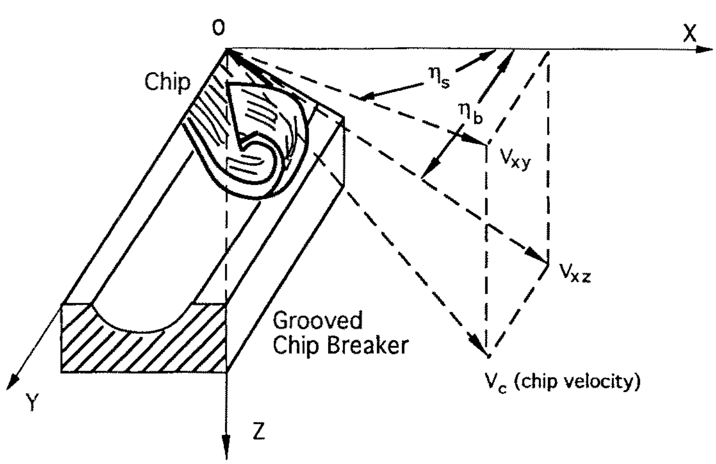


Fig. 1. Three dimensional (3D) chip flow with a grooved chip breaker.

3. Database Structure

Development of a comprehensive database system is the basis for chip-groove design using a knowledge-based approach and this provides an analytical foundation for chip breaking performance, and power consumption rates, and contributes to the development of knowledge rules and design criteria for grooved chip breakers. The database system developed for this purpose consists of four parts: reference database, grooved chip breaker database, natural contact length database and 3D chip flow database, which are used as a reference system for quantifiable comparison.

3.1 Reference Database

A series of experiments were conducted by using restricted contact secondary rake tools (as the standard tools) for a wide range of cutting speeds, undeformed chip thicknesses, tool rake angles and tool restricted contact lengths. Medium carbon steel was used as the work material in the experiments. The chip backflow angle η_b, chip thickness t_2 and the main cutting force F_c, measured from the experiments, were recorded to set up the reference database.

3.2 Grooved Chip Breaker Database

Four chip-groove styles (*A* for raised backwall, *B* for standard backwall, *C* for reduced backwall and *D* for no backwall) as shown in Fig. 2, each with three groove sizes (GT1 for large, GT2 for medium and GT3 for small), were used in the experiments to establish the effects of different groove profiles for various t_1 and h values for a cutting speed V = 100 m/min, rake angle $\alpha = 0°$ and width of cut w = 3.0 mm. The main cutting force F_c, chip breaking performance and chip forms/shapes were recorded to set up the grooved chip breaker database.

3.3 Natural Contact Length Database

A series of tool/chip natural contact lengths, h_n, was determined from the experimental η_b vs. h relationship diagrams (see Fig. 3 for typical relationships) under a given set of cutting conditions and tool geometry. In Fig. 3, h_n is the value of h when the chip backflow angle η_b is equal to the tool rake angle α (i.e. when the chip flows straight along the rake face). On the basis of the reference database, h_n values were estimated for combinations of 4 cutting speeds, 3 undeformed chip thicknesses and 5 tool rake angles and were then stored in the natural contact length database.

3.4 3D Chip Flow Database

A first series of oblique machining experiments was conducted with standard grooved chip breakers for combinations of 3 work materials, 3 tool nose radii, 5 depths of cut and 6 feeds at a cutting speed of V = 100 m/min, tool inclination angle $\lambda = -6°$ and rake angle $\alpha = -5°$. The chip-sideflow angle η_s

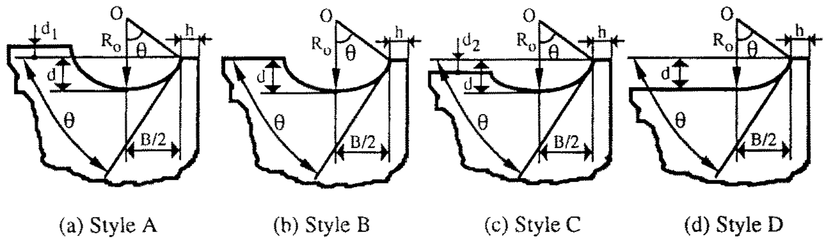


Fig. 2. Configurations of grooved chip breakers.

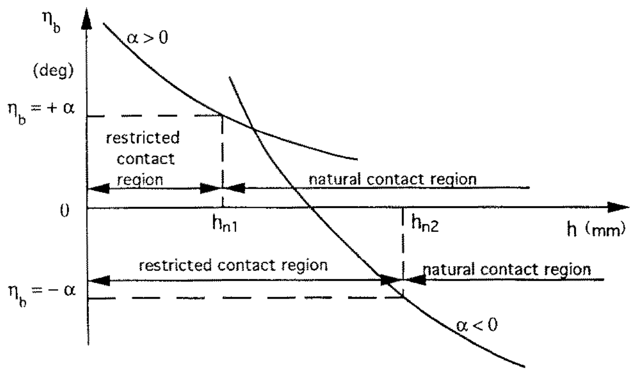


Fig. 3. Determination of tool/chip natural contact lengths from η_b vs. h relationship.

and chip-backflow angle η_b were measured simultaneously by two still-photographic cameras (Olympus OM-10 with zoom lens and close-up filters) mounted in two mutually perpendicular planes [33]. The tool inserts were ground properly in order to enable the cameras to "see" into the chip groove. Chips were collected after each test to measure the mean thickness t_2. A second series of experiments was conducted to establish the effects of tool inclination angle λ and cutting speed V on chip-sideflow angle η_s. The machining conditions used in the experiments are shown in Table 1. The experimental results were combined to establish a 3D chip flow database.

4. Summary of the Present Knowledge for Establishing a Knowledge Base

Having recognised the need for gathering the relevant scattered knowledge, an attempt is made to extract and summarise previous research findings in four major groups, which are designed to facilitate the setting up of a knowledge base.

4.1 Analysis of Chip Backflow Angle

From the series of machining experiments conducted with secondary rake restricted contact tools to study the individual effects of undeformed chip thickness t_1, restricted contact length h, rake angle α and cutting speed V, several relationships were established. The interrelationships between these parameters and the chip backflow angle η_b were incorporated into the database. A general description of these observed effects is shown in Fig. 4.

4.2 Analysis of Power Consumption

For a given set of cutting conditions, the minimum power consumption for grooved chip breakers can be achieved by selecting the appropriate restricted contact length h, groove size and groove style. Fig. 5 gives a representative diagram from a series of machining experiments conducted for studying the effect of tool/chip contact length on the main cutting force under a fairly wide range of cutting conditions and tool geometry. At a given t_1 value, an increase in the tool/chip contact length increases the cutting forces within the restricted contact region, while the cutting forces remain constant with increase in contact length in the natural contact region. Experiments at varying cutting speeds and tool rake angles have indicated this effect consistently, thus providing a clear message that reduced contact length within the restricted contact region is the key to reduced power consumption.

However, the power consumption rate is different when using different chip-groove sizes and styles, as shown in Fig. 6 for a set of typical relationships between specific cutting pressure P_s and restricted contact length h. There exist minimum power regions for all three chip-groove sizes, depending on the chip-groove utilisation. The h value is a major factor determining the chip-groove utilisation owing to its significant effect on the chip backflow angle η_b. For all three chip-groove sizes, the differences in power consumption between all groove styles (A, B, C and D) are very marked and this effect can be explained in terms of the groove geometry and the corresponding utilisation of these grooves by the chip.

4.3 Analysis of Chip Breaking Performance

The chip breaking performance can be estimated by the total effects of the chip backflow angle η_b, the groove size and the groove style.

(a) Effect of Tool Restricted Contact Length

As seen from Fig. 7, lower h values associated with higher chip backflow angles result in reduced chip up-curl radius, producing tighter and more efficiently broken chips.

(b) Effect of Groove Sizes

On the basis of the analysis of chip up-curl radius, it can be seen that the chip breaker with a smaller groove size produces better chip breakability owing to the smaller chip up-curl

Table 1. Machining conditions used for setting up 3D chip flow database.

First series of machining experiments	
Work materials	Low carbon steel: BHN = 140 (C 0.25% Mn 0.8% Si 0.4%) Medium carbon steel: BHN = 160 (C 0.4% Mn 0.75% Si 0.27%) High carbon steel: BHN = 225 (C 1.0% Cr 1.25%)
Tool nose radius	r = 0.4 mm, *r* = 0.8 mm and *r* = 1.2 mm
Chip breaker type	Modified standard groove-type chip breakers
Cutting conditions	Depth of cut, d = 0.5, 1.0, 2.0, 3.0, 4.0 mm Feed, f = 0.04, 0.1, 0.2, 0.3, 0.4, 0.5 mm/rev Cutting speed, V = 100 m/min
Second series of machining experiments	
Cutting speed	V = 50, 80, 125, 170, 225, 300 m/min
Tool inclination angle	λ = −14°, −12°, −6°, −3°, −0°, 2°, 5°,
Depth of cut = 0.5–3.0 mm Feed = 0.1–0.3 mm/rev Tool nose radius = 0.8 mm Work material = medium carbon steel Chip breaker type = standard groove tool	

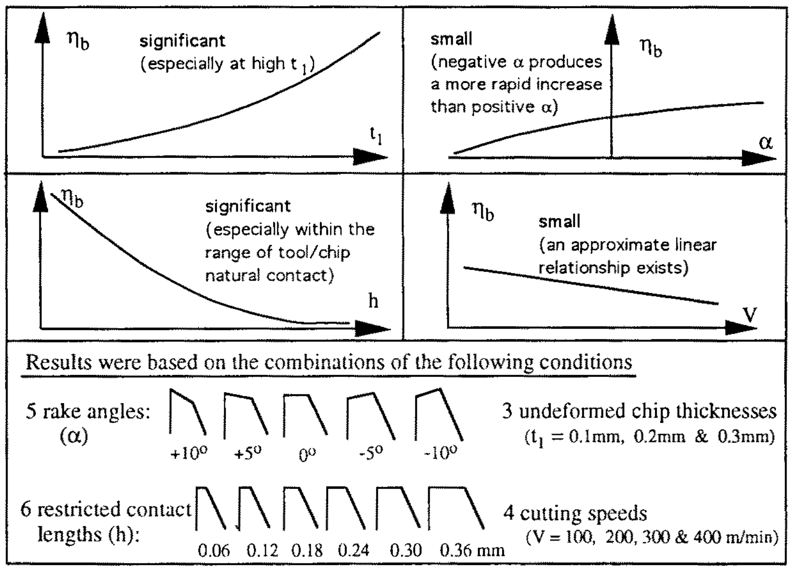


Fig. 4. General trends of the effects of various variables on chip backflow angle.

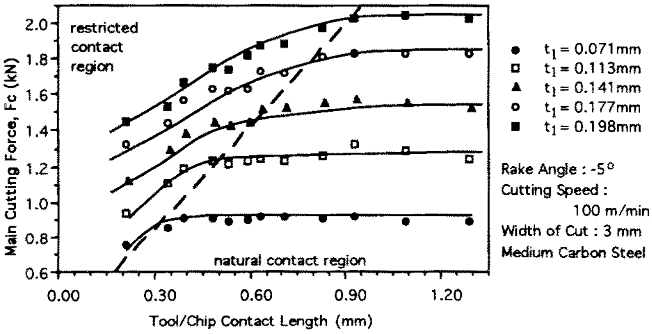


Fig. 5. The effect of tool/chip contact length on main cutting force.

radius which makes the chip break more easily. Fig. 8 shows the variation of chip up-curl radius with tool restricted contact length for the three groove sizes tested. It also appears that minimum chip up-curl radius r_u equalling the chip-groove radius R_0 will occur when the restricted contact length h is small enough to make the chip utilise the entire chip-groove.

(c) Effect of Groove Styles

A representative photograph of the chip breaking patterns with varying groove styles observed is given in Fig. 9. The chip breaker with a raised backwall (i.e. Style *A* in Fig. 2) produces the best chip breakability with only one full-turn chip, while the chip breaker without a backwall (i.e. Style *D* in Fig. 2) gives the poorest chip breakability.

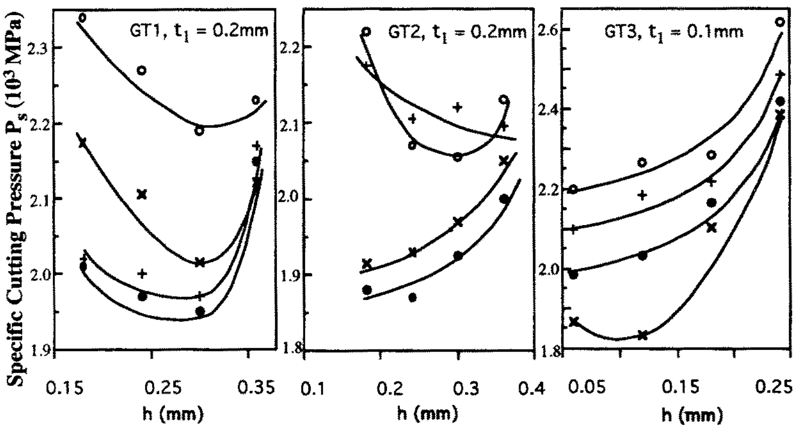


Fig. 6. The effect of tool restricted contact length on specific cutting pressure in machining with grooved chip breakers.

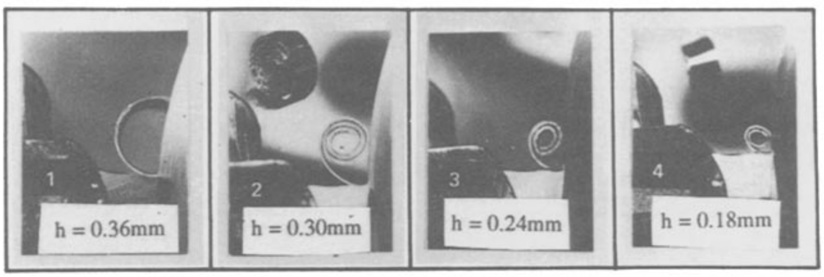


Fig. 7. The effect of tool restricted contact length on chip up-curl and chip breaking.

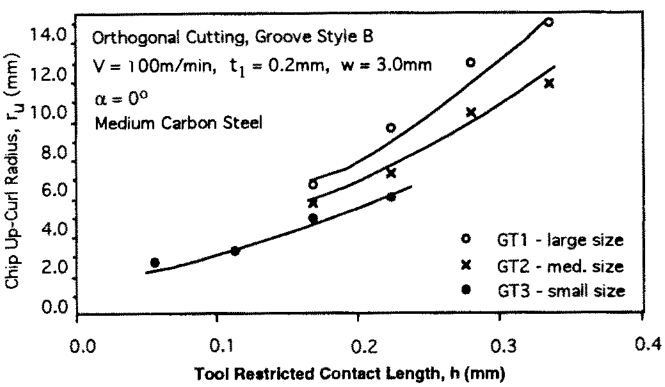


Fig. 8. The effect of chip-groove size of on chip up-curl radius.

4.4 Effects of Various Factors on 3D Chip Flow, Curl and Breaking

(a) The Effect of Depth of Cut

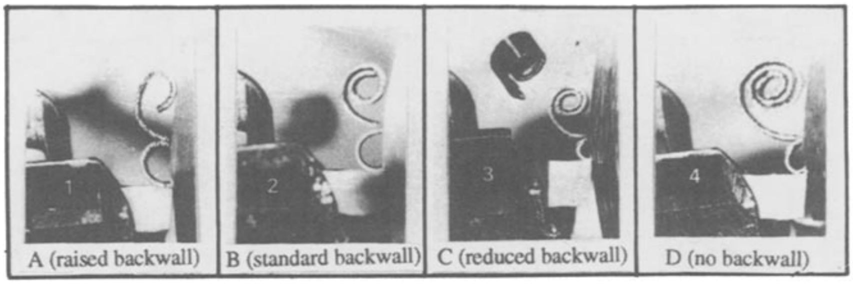
As seen from Fig. 10(*a*), an increase in depth of cut (d) increases the effective chip thickness, and thus improves chip breakability at low depths of cut, but when the depth of cut is larger than 2 mm, this effect is insignificant. The depth of cut has a greater influence on the chip sideflow angle η_s. When the depth of cut is less than or approximately equal to the tool nose radius, the chip-sideflow angle η_s is large, while at larger depths of cut, there is a rapid decrease in η_s (see Fig. 10(*b*)). Variations of depth of cut have almost no influence on the chip-backflow angle η_b (Fig. 10(*c*)).

(b) The Effect of Feed

The feed (f) plays a significant role in the chip breaking performance. Increasing the feed increases chip-sideflow angle η_s, chip-backflow angle η_b and chip thickness t_2 for all cutting conditions tested (see a typical set of results in Fig. 11).

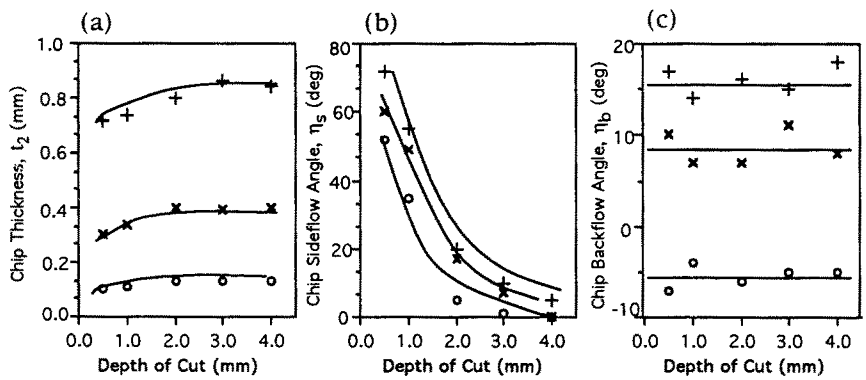
(c) The Effect of Tool Nose Radius

The effect of tool nose radius (r) on chip breakability is reduced as the depth of cut increases. As shown in Fig. 12(*a*), the cutting tool with a sharper nose has better chip breakability owing to the larger chip thickness produced. For a given depth of cut, a larger tool nose radius always corresponds to



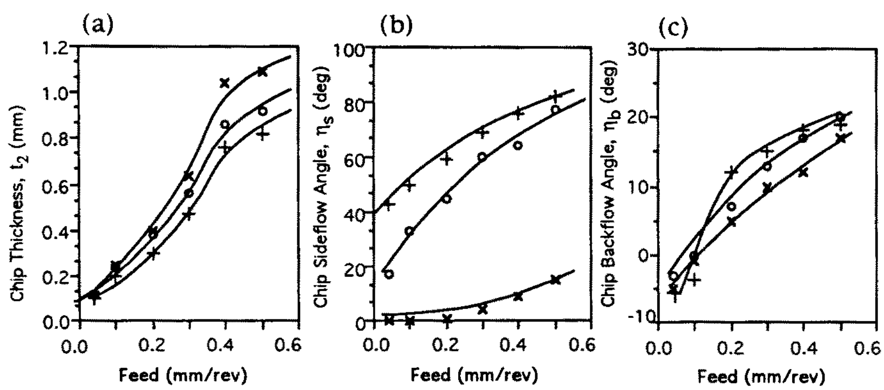
Orthogonal Cutting	:	V = 100m/min, t_1 = 0.2mm, w = 3.0mm, $\alpha = 0^o$
Chip-groove Size	:	Medium (GT2), h = 0.3mm
Work Material	:	Medium Carbon Steel

Fig. 9. The effect of chip-groove styles on chip breaking patterns.



Work Material : Medium Carbon Steel	o	Feed (f) = 0.04 mm/rev
Tool Nose Radius (r) = 1.2 mm	x	Feed (f) = 0.20 mm/rev
Rake Angle (α) = -5^o	+	Feed (f) = 0.40 mm/rev
Cutting Speed (V) = 100 m/min		

Fig. 10. The effects of depth of cut.



Work Material : Medium Carbon Steel	+	Depth of Cut (d) = 0.5 mm
Tool Nose Radius (r) = 0.8 mm	o	Depth of Cut (d) = 2.0 mm
Rake Angle (α) = -5^o	x	Depth of Cut (d) = 4.0 mm
Cutting Speed (V) = 100 m/min		

Fig. 11. The effects of feed.

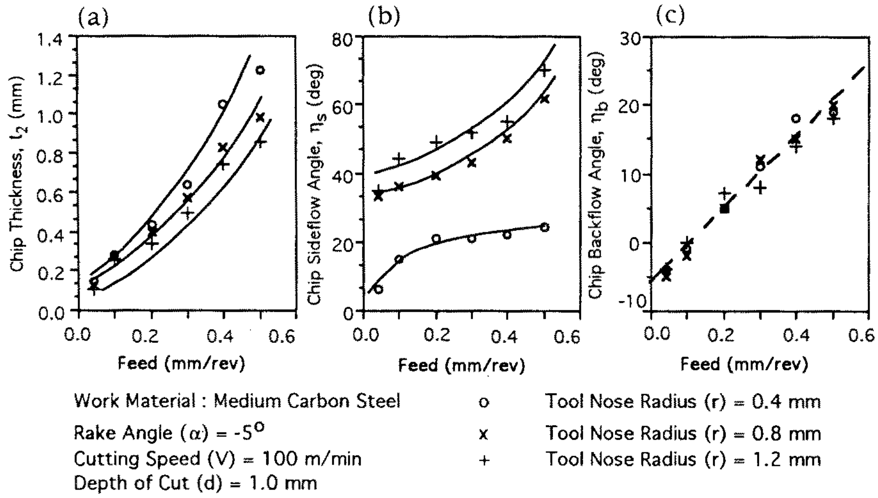


Fig. 12. The effects of tool nose radius.

a higher chip-sideflow angle η_s and such an influence tends to increase with increasing feed (Fig. 12(*b*)). The effect of tool nose radius on chip backflow angle η_b is insignificant.

(d) The Effect of Work Material

In general, steels with higher carbon content produce thinner chips (see Fig. 13). Thinner chips are generally more difficult to break. Chip thickness variations are more significant at higher feeds. However, the chip-sideflow angle η_s and chip-backflow angle η_b are not sensitive to variations of the work materials tested (low, medium and high carbon steels). The effects of alloying have not been studied extensively in the present work, however, it is considered that the variations in the work-material hardness values could be used to represent approximately the work-material property variations, although more detailed fundamental studies may be required to update and validate this knowledge.

(e) The Effects of Tool Inclination Angle and Cutting Speed

Experimental results show that the relationship between the tool inclination angle λ and chip-sideflow angle η_s appears to be approximately linear under different cutting conditions. The experimental work with different tool inclination angles, depths of cut and feeds also shows that variations of cutting speed V have either only a slight effect or no effect on the chip-sideflow angle η_s.

4.5 Analysis of 3D Chip Flow and Curling with Grooved Chip Breakers

(a) Effect of Chip-backflow Angle

The chip-backflow angle η_b plays a key role in chip-groove utilisation, which determines the chip breakability and power

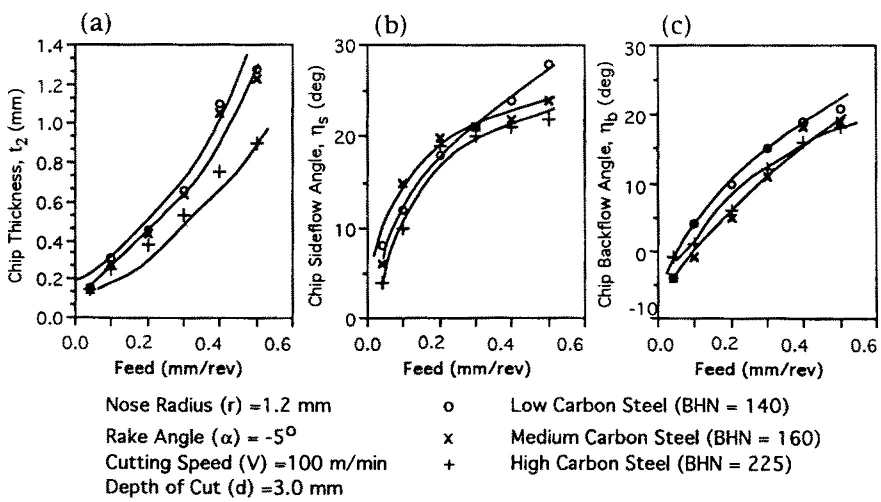


Fig. 13. The effects of work material (carbon steels).

consumption rates. Fig. 14 shows a typical chip curling pattern in the case of a grooved chip breaker with restricted contact length (i.e. $h < h_n$). It is apparent from this figure that the smaller is the chip up-curl radius r_u, the greater is the chip-groove utilisation. The chip may fully utilise the groove profile when the chip up-curl radius r_u is equal to the groove radius R_0,

$$r_u = r_{u\,min} = R_0 = B/(2\sin\theta) \quad (2)$$

where θ is the groove tangent angle which has a very close relationship to the chip-backflow angle η_b. Therefore, it can be concluded from Eq. (2) that when the chip backflow angle $\eta_b = \theta$, the chip may fully utilise the groove profile, i.e. the chip curls with $r_{u\,min}$ within a specified groove profile. If $\eta_b > \theta$, there will be additional friction between the chip and the groove surface, thus consuming more power. Further, there is always a certain amount of elastic recovery, although it is assumed that the chip is plastically deformed when leaving the tool restricted contact to enter the groove. Therefore, in designing, $(\eta_b - \alpha)/\theta = 1.2$ could be taken as the norm in order to guarantee the full utilisation of the groove profile.

It has been shown from the use of high-speed filming techniques for the actual chip breaking process that the chip up-curl radius (r_u) varies within a chip breaking cycle [34]. This variation results in the variation of chip-groove utilisation. Therefore, the term "full utilisation of the groove" has to be interpreted as the "maximum allowable utilisation of the chip breaker groove".

(b) Effect of Chip-sideflow Angle

In three-dimensional oblique cutting, the effectiveness of grooved chip breakers is reduced owing to the effect of chip-sideflow angle η_s. As shown in Fig. 15, when the chip sideflow angle η_s is not equal to zero, the equivalent tool restricted contact length h_e and the equivalent groove width B_e are larger than h and B, respectively, i.e.

$$h_e = h/\cos\eta_s, \quad B_e = B/\cos\eta_s \quad (3)$$

The chip-groove profile will be of no use if the equivalent restricted contact length h_e is larger than the tool natural contact length h_n, and also when η_s is large, say, 75°, h_e and

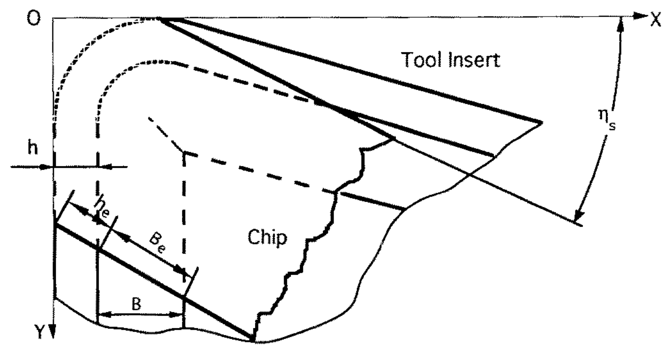


Fig. 15. The chip sideflow effect on effective chip-groove parameters.

B_e will increase rapidly even with a small increase in η_s. In this case, the direction of chip-sideflow will be nearly parallel to the cutting edge. Therefore, a standard grooved chip breaker is no longer usable for chip curling under these conditions.

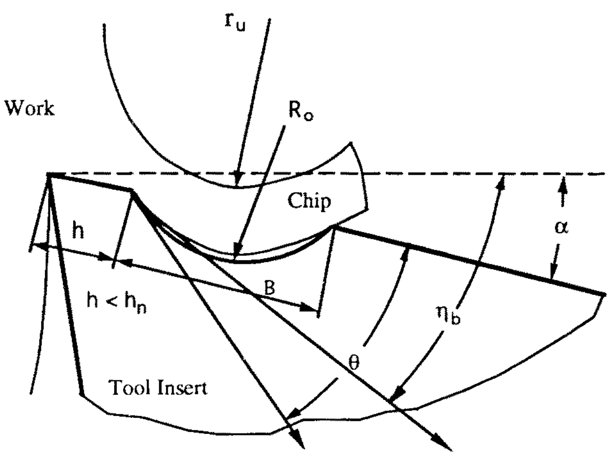


Fig. 14. The chip backflow effect on chip-groove utilisation.

5. Establishment of a Knowledge Base

5.1 Knowledge Rules for Power Consumption

(a) Rules for Setting up the Restricted Contact Length – Power Consumption Relationship

In the experiments for setting up the grooved chip breaker database, six values of restricted contact length h (0.36, 0.30, 0.24, 0.18, 0.12 and 0.06 mm) were used at V = 100 m/min, and α = 0°. The effect of variation of h on power consumption under various cutting conditions is summarised in the form of a set of knowledge rules. The general format of such rules is given below,

IF $h = h_i$ (a non-standard value in the grooved chip breaker database)
THEN the power consumption will increase by ΔP_h (if $\Delta P_h > 0$) or decrease by ΔP_h (if $\Delta P_h < 0$) compared with that at a standard h value in the grooved chip breaker database,

where ΔP_h is defined as the differential amount of power consumption due to the restricted contact length.

(b) Rules for Setting up the Rake Angle – Power Consumption Relationship

The effect of rake angle α on power consumption appears to vary under different h values. If the power consumption at α = 0° is taken as the standard value, the relative variation of power consumption for various rake angle values can be deduced from the reference database. The general format of such rules is given below,

IF $\alpha = \alpha_i$ (a non-standard value in the reference database)

THEN the power consumption will increase by ΔP_α (if $\Delta P_\alpha > 0$) or decrease by ΔP_α (if $\Delta P_\alpha < 0$) compared with that at a standard α value in the reference database,

where ΔP_α is defined as the differential amount of power consumption due to the rake angle.

(c) Rules for Setting up the Cutting Speed – Power Consumption Relationship

The effect of cutting speed V on power consumption is similar to that of rake angle α. The general format of knowledge rules is given below,

IF $V = V_i$ (a non-standard value in the reference database)
THEN the power consumption will increase by ΔP_V (if $\Delta P_V > 0$) or decrease by ΔP_V (if $\Delta P_V < 0$) compared to that at a standard V value in the reference database,

where ΔP_V is defined as the differential amount of power consumption due to the cutting speed.

(d) Rules for Determining the h Values for Minimum Power Consumption

The restricted contact length h is the most important parameter for grooved chip breakers. Generally speaking, the smaller the h value, the lower the power consumption. However, this is not always true when dealing with a groove profile. The reason for this is that a decrease in h may cause an increase in η_b and if the η_b value is excessive it will consume more power. Based upon the established grooved chip breaker database, the rules for determining h values (h_P) for minimum power consumption are summarized. A typical rule is given below:

IF chip-groove size is large (GT1) and chip-groove style is A
THEN the chip-groove is suitable for larger t_1 values ($t_1 > 0.1$ mm) and the power consumption is minimum for
$h_P = 0.30$ mm for medium t_1 values ($0.1 < t_1 < 0.3$ mm) or
$h_P = 0.36$ mm for high t_1 values ($t_1 \geq 0.3$ mm).

5.2 Knowledge Rules for Chip Breakability

(a) Representative Rules for the Selection of Chip-groove Sizes and the h Values (h_c)

The selection of restricted tool contact length (h) for different chip groove sizes and styles is essential to guarantee effective chip breaking at minimum power consumption. In this work, a criterion is applied, from the view point of chip breakability, as $h_c = bh_n < h_n$ with the factor b being smaller than 1. The factor b is estimated approximately based on a judgement of the combined effects of chip-groove sizes, chip-groove styles, cutting conditions and chip sideflow angle which will vary the equivalent h value, i.e. h_e, as presented by equation (3).

(i) IF t_1 value is low (i.e. $t_1 \leq 0.1$ mm)
THEN small groove size (GT3) must be selected with $h_c = 0.5h_n$.

(ii) IF t_1 value is medium (i.e. $0.1 < t_1 < 0.3$ mm)
THEN medium groove size (GT2) is selected with $h_c = 0.6h_n$ or
small groove size (GT3) is selected with $h_c = 0.7h_n$.

(iii) IF t_1 value is high (i.e. $t_1 \geq 0.3$ mm)
THEN large groove size (GT1) is selected with $h_c = 0.7h_n$ or
medium groove size (GT2) is selected with $h_c = 0.8h_n$.

(b) Representative Rules for the Selection of Chip-groove Styles (A, B, C and D)

In the present work, a chip-groove style can be chosen from four commonly used styles (A for raised, B for standard, C for reduced and D for no backwalls), each with different groove sizes and tool restricted contact lengths.

(i) IF all the cutting conditions are same
THEN chip breakability is in decreasing order for chip-groove styles (from A to D) for any given chip-groove size.

(ii) IF t_1 value is low ($t_1 \leq 0.1$ mm), chip breakability is usually a problem
THEN the preferential selection of chip-groove styles is from A to D.

(iii) IF t_1 value is high ($t_1 \geq 0.3$ mm), chip breakability is usually not a problem
THEN the chip-groove style with minimum power consumption is preferred.

(iv) IF t_1 value is medium ($0.1 < t_1 < 0.3$ mm), the integrated effects of chip breakability and power consumption should be considered
THEN when the difference in power consumption is less than 25%, the chip-groove style with better chip breakability is preferred.

5.3 Knowledge Rules for Predicting the Chip-backflow Angle

The restricted contact length h, tool rake angle α, feed f, and cutting speed V have significant influence on chip backflow angle η_b.

(a) Rules for the Effect of Restricted Contact Length

The chip backflow angle η_b is sensitive to small variations of restricted contact length h. A set of rules have been summarised to predict η_b for all possible h values under various cutting conditions based on the reference database. The general format of such rules is given below.

IF $h = h_i$ (a non-standard value in the reference database)
THEN the chip backflow angle η_b will increase by $\Delta\eta_{bh}$ (if $\Delta\eta_{bh} > 0$) or decrease by $\Delta\eta_{bh}$ (if $\Delta\eta_{bh} < 0$) compared with a standard h value in the reference database,

where $\Delta\eta_{bh}$ is defined as the differential amount of chip backflow angle due to the restricted contact length.

(b) Rules for the Effect of Rake Angle

Knowledge rules for the effect of rake angle α on the chip backflow angle η_b are summarised based on the comparison with the standard rake angle value, $\alpha = 0°$, at different machining conditions. The general format of the knowledge rules is given below.

IF $\alpha = \alpha_i$ (a non-standard value in the 3D chip flow database)
THEN the chip backflow angle η_b will increase by $\Delta\eta_{b\alpha}$ (if $\Delta\eta_{b\alpha} > 0$) or decrease by $\Delta\eta_{b\alpha}$ (if $\Delta\eta_{b\alpha} < 0$) compared with that at a standard α value in the 3D chip flow database,

where $\Delta\eta_{b\alpha}$ is defined as the differential amount of chip-backflow angle η_b due to the rake angle α.

(c) Rules for the Effect of Cutting Speed

Taking cutting speed V = 100 m/min as the standard value for comparison, knowledge rules for the effect of V on η_b have been developed. The general format of these rules is given below.

IF $V = V_i$ (a non-standard value in the 3D chip flow database)
THEN the chip backflow angle η_b will increase by $\Delta\eta_{bV}$ (if $\Delta\eta_{bV} > 0$) or decrease by $\Delta\eta_{bV}$ (if $\Delta\eta_{bV} < 0$) compared with that at a standard V value in the 3D chip flow database.

where $\Delta\eta_{bV}$ is defined as the differential amount of chip-backflow angle η_b due to the cutting speed V.

(d) Rules for the Effect of Feed

The feed f has a significant effect on chip-backflow angle η_b. Six feed values (0.04, 0.1, 0.2, 0.3, 0.4, 0.5 mm/rev) are selected as standard values in the established 3D chip flow database. The general format of the rules for the effect of feed on η_b is given below.

IF $f = f_i$ (a non-standard value in the 3D chip flow database)
THEN the chip backflow angle η_b will increase by $\Delta\eta_{bf}$ (if $\Delta\eta_{bf} > 0$) or decrease by $\Delta\eta_{bf}$ (if $\Delta\eta_{bf} < 0$) compared with that at a standard f value in the 3D chip flow database,

where $\Delta\eta_{bf}$ is defined as the differential amount of chip-backflow angle η_b due to the feed f.

5.4 Knowledge Rules for Predicting the Chip-sideflow Angle

The tool nose radius r, tool inclination angle λ, depth of cut d and feed f are among the major factors influencing the chip-sideflow angle η_s in oblique machining.

(a) Rules for the Effect of Tool Nose Radius

The tool nose radius r plays a significant role in determining chip sideflow angle η_s. The general format of the rules for the effect of tool nose radius on η_s is given below.

IF $r = r_i$ (a non-standard value in the 3D chip flow database)
THEN the chip sideflow angle η_s will increase by $\Delta\eta_{sr}$ (if $\Delta\eta_{sr} > 0$) or decrease by $\Delta\eta_{sr}$ (if $\Delta\eta_{sr} < 0$) compared with that at a standard r value in the 3D chip flow database,

where $\Delta\eta_{sr}$ is defined as the differential amount of chip sideflow angle η_s due to the tool nose radius r.

(b) Rules for the Effect of Tool Inclination Angle

In formulating the knowledge rules for the effect of inclination angle, $\lambda = 0°$ is taken as the standard value for comparison. An example of such rules is shown as follows:

IF Work material is medium carbon steel and $\lambda = \lambda_1 > 0°$
THEN Chip-sideflow angle η_s will have an increment of $\eta_{s\lambda} = 1.15\lambda_1$.

(c) Rules for the Effect of Depth of Cut

The depth of cut d has a significant influence on chip-sideflow angle η_s. Five depth-of-cut values (0.5, 1.0, 2.0, 3.0 and 4.0 mm) were selected as the standard values. The general format of such rules is given below.

IF $d = d_i$ (a non-standard value in the 3D chip flow database)
THEN the chip sideflow angle η_s will increase by $\Delta\eta_{sd}$ (if $\Delta\eta_{sd} > 0$) or decrease by $\Delta\eta_{sd}$ (if $\Delta\eta_{sd} < 0$) compared with that at a standard d value in the 3D chip flow database,

where $\Delta\eta_{sd}$ is defined as the differential amount of chip sideflow angle η_s due to the depth of cut d.

(d) Rules for the Effect of Feed

Knowledge rules for the effect of feed f on chip-sideflow angle η_s are derived based on the selected six standard feed values. The general format of such rules is given below.

IF $f = f_i$ (a non-standard value in the 3D chip flow database)
THEN the chip sideflow angle η_s will increase by $\Delta\eta_{sf}$ (if $\Delta\eta_{sf} > 0$) or decrease by $\Delta\eta_{sf}$ (if $\Delta\eta_{sf} < 0$) compared with that at a standard f value in the 3D chip flow database.

where $\Delta\eta_{sf}$ is defined as the differential amount of chip sideflow angle η_s due to the feed f.

6. A General Strategy for Designing Effective Grooved Chip Breakers

The design of an effective grooved chip breaker greatly depends on how the groove profile is utilised in order to achieve effective chip breaking at minimum power consumption.

6.1 Determining the Optimum Restricted Contact Length (*h*)

As discussed above, the appropriate selection of h value is very important for efficiency. A very small h value will weaken the strength of the tool cutting edge, furthermore, it might consume more power when machining with a specific grooved chip breaker, mainly owing to the excessive chip-backflow angle η_b. Fig. 16(a) shows a typical $\eta_b - h$ relationship from the experiments. When $h < h_n$, the chip will flow towards the groove with an effective chip-backflow angle η_{be}. Also h_c is the assumed h value from the effective chip-breaking point of view. Fig. 16(b) shows a typical $P_s - h$ relationship from the experiments, where there exists a specific h value (h_P) at which the power consumption reaches its minimum value. In the region where $h > h_P$, the power consumption reduces with decreasing h, while in the region of $h < h_P$, the effect is opposite. The curve in this region is, however, not as steep as that in the region for $h > h_P$. Therefore, the optimum h value is determined by the following relationship (h_c and h_P are determined by the corresponding rules):

$$h = \{\min(h_c, h_P)\}\cos\eta_s \tag{4}$$

where the chip-sideflow angle η_s can be estimated based on the 3D chip flow database and the associated knowledge rules. If $\eta_{s(std)}$ is assumed to be the standard chip-sideflow angle in the 3D chip flow database, then η_s can be determined by the following equation:

$$\eta_s = \eta_{s\lambda} + (1 + \Delta\eta_{sr})(1 + \Delta\eta_{sd})(1 + \Delta\eta_{sf})\eta_{s(std)} \tag{5}$$

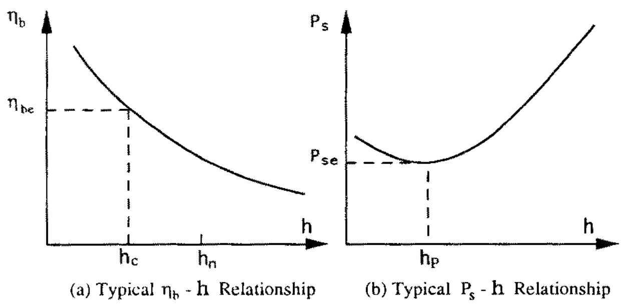


Fig. 16. Determination of the optimum restricted contact length.

6.2 Determining the Effective Groove Parameters

For a given restricted contact length h corresponding to a set of input cutting conditions, the chip-backflow angle η_b can be predicted using the knowledge rules and the established 3D chip flow database. If $\eta_{b(std)}$ is assumed to be the standard chip-backflow angle in the 3D chip flow database, then the predicted chip-backflow angle η_b is given as follows:

$$\eta_b = (1 + \Delta\eta_{bh})(1 + \Delta\eta_{bd})(1 + \Delta\eta_{b\alpha})(1 + \Delta\eta_{bf})\eta_{b(std)} \tag{6}$$

In oblique machining with 3D chip flow and chip breaking, the design of effective chip breakers should consider the relationship between the depth of cut and tool nose radius in order to achieve the optimal use of chip-groove profile, particularly in the case of finish-turning where the depth of cut is usually smaller than the tool nose radius used. However, in the cutting region of the tool nose which forms a curved cutting edge, the effect of restricted tool contact is very complex [3] and there is a need to consider an equivalent tool restricted contact length (h_e), since the h value varies along the curved cutting edge owing to the effect of chip-sideflow angle η_s. This indicates that the chip backflow angle η_b varies at different sections of the curved cutting edge for the same chip section. It is extremely difficult at the moment to obtain experimentally such precise knowledge owing to the very complex mechanism involved. Therefore, the chip backflow angle η_b was measured in this work only from the straight cutting portion of the tool insert based on the assumption that minimum variation occurs in the chip backflow along the curved cutting edge.

Also, by considering the fact that the actual chip is a whole entity (not fragmented), an assumption is made in this work that the chip enters the chip-groove around the tool nose with a mean chip backflow angle η_{bm}. In order to determine the mean value of equivalent restricted tool contact length h_{em} along the curved cutting edge, a polar coordinate system, the origin O of which coincides with the tool nose centre N_R, is introduced, as shown in Fig. 17. Owing to the symmetry of various tool insert shapes, the polar angle β varies from 0 to a maximum angle equal to half the tool nose angle, for example, $\beta_{max} = 30°$ for TNMG (triangular) inserts, $\beta_{max} = 45°$ for SNMG (square) inserts, $\beta_{max} = 40°$ for CNMG (diamond) inserts, etc. For a small depth of cut which generates a large chip sideflow angle η_s, when $\beta = 0°$, the h_e value is maximum and equal to $h/\cos\eta_s$; and when $\beta = \beta_{max}$, the h_e value is a minimum and very close to h. Therefore, it is reasonable to assume that the h_{em} value can be found to exist at approximately $\beta = \frac{1}{2}\beta_{max}$. With such an assumption, h_{em} can be determined by the following second-order equation which would result from the geometric relation (cosine theorem) in the triangle ΔAOB shown in Fig. 17.

$$(r - h)^2 = h_{em}^2 + r^2 - 2 \cdot h_{em} \cdot r \cdot \cos(\eta_s - \tfrac{1}{2}\beta_{max}) \tag{7}$$

In order to achieve effective chip breaking at minimum power consumption in 3D machining modes, different chip-groove parameters are required at the straight and curved cutting edges respectively. Based on the above analysis, the calculation of chip-groove parameters is summarised and

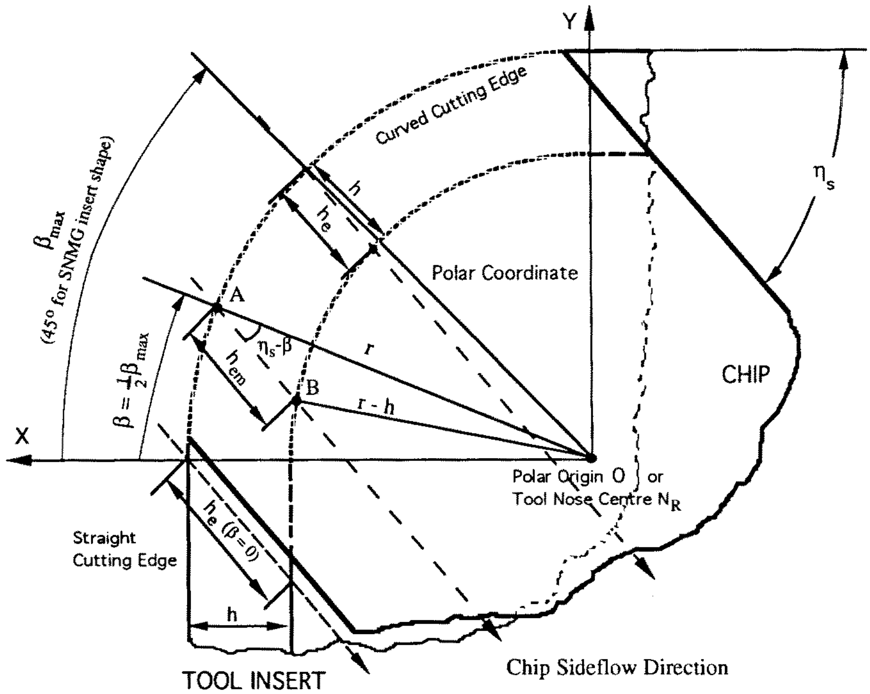


Fig. 17. Effect of tool restricted contact on the tool nose area (based on an SNMG tool insert shape).

categorised into three typical machining conditions, i.e. finish turning, medium turning and heavy turning as shown in Table 2.

6.3 A General Procedure for Designing Effective Grooved Chip Breakers

On the basis of the established knowledge-based system for designing effective grooved chip breakers, a schematic diagram describing the general procedure for determining the most effective tool restricted contact length h as well as the groove parameters has been prepared and is illustrated in Fig. 18. This system has been developed using the Turbo PROLOG language.

7. Concluding Remarks

From the above analysis for designing effective chip breakers, the following major conclusions can be drawn.

Table 2. Determination of effective chip-groove parameters.

	Finish turning	Medium turning	Heavy turning
Groove tangent angle	At straight cutting edge: $\theta = \frac{\eta_b - \alpha}{1.2}$ At curved cutting edge: $\theta = \frac{\eta_{bm} - \alpha}{1.2}$		
Groove width	Small: B = 1.0 mm	Medium: B = 1.5 mm	Large: B = 2.0 mm
Groove radius	$R_0 = \frac{B}{2\sin(\theta)}$		
Groove depth	$d = R_0 - \sqrt{(R_0^2 - (B/2)^2)}$		
Groove backwall	Raised height $d_1 = (0.3\text{–}0.7)d$ (A more raised height corresponds to a better chip breakability but a higher power consumption.)	Standard backwall (no raised or reduced)	Raised height $d_2 = (0.2\text{–}0.5)d$ (A more reduced height corresponds to a poorer chip breakability but a lower power consumption.)

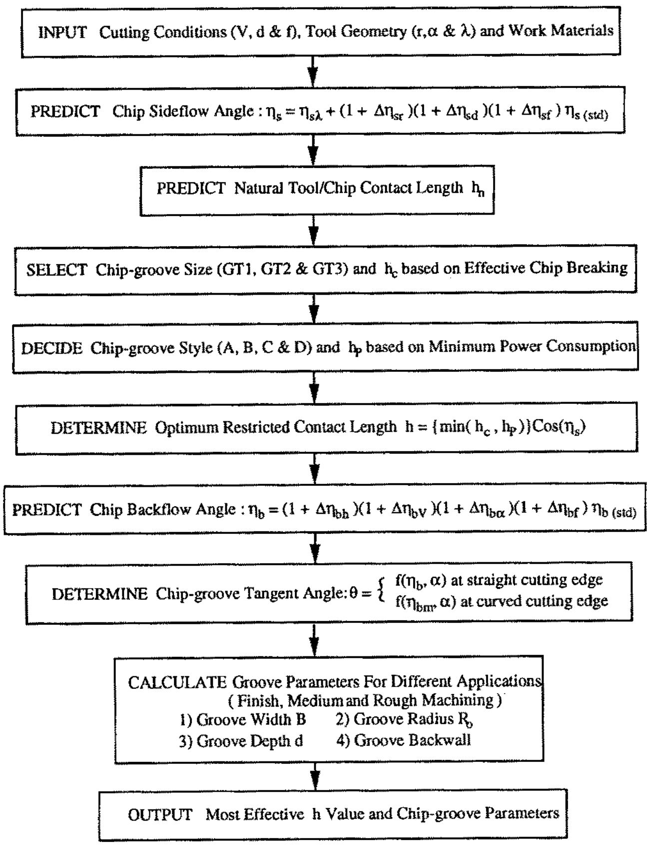


Fig. 18. The schematic diagram for designing effective grooved chip breaker.

1. Most commercially available cutting-tool inserts are designed on the basis of the traditional "try and see" methods which are non-systematic, unscientific and time-consuming. Also, these methods very often do not provide the best results. Therefore, it is necessary to explore a more scientific design strategy in order to facilitate improved utilisation and performance of cutting tool inserts in machining.
2. This paper presents an alternative to the traditional design of chip breakers, in the form of a knowledge-based system incorporating a set of four databases: reference database, tool natural contact length database, grooved chip breaker database, and 3D chip flow database. By using these databases, the optimal chip-groove design parameters can be estimated to achieve effective chip breaking at minimum power consumption in 3D machining modes.
3. In the present work, conventional grooved chip breakers are selected as typical tools since the basic analysis of the use of these tools could be regarded as a suitable basis for the general chip breaker design. The combined effects of restricted tool contact and groove configurations have been studied systematically in terms of three-dimensional (3D) chip flow. It has been shown that effective chip breaking at minimum power consumption can be achieved through the optimum groove utilisation of the chip breakers.
4. Although the knowledge-based system is only for designing effective standard grooved chip breakers, the methodology described in this paper could be extended to the design of more complex toolface configurations, with suitable selection and adaptation of chip breaker features incorporating non-standard grooves, bumps, etc. However, a thorough understanding of the effects of these features would be necessary to develop appropriate knowledge rules.

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