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Review

A review of the chip breaking methods for continuous chips in turning

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ABSTRACT

The reliability of continuous turning process is a significant necessity of mass production and automatic manufacturing systems. Long chips are the main problems for the continuous turning operations and chip break is difficult during the machining of ductile steel and superalloys. Chip formation during machining negatively affects worker and tool safety, workpiece quality, tool life, and energy consumption while also reducing operational efficiency. To alleviate such problems, continuous chips formation during machining must be controlled through chip breaking. As part of this study, various chip breaker designs and approaches to chip breaking were evaluated. The study analyzes the problems associated with continuous chips and compiles knowledge of the mechanics involved in, and the methods developed to handle chip breaking. The methods for breaking continuous chips were categorized into five sections. Different methods were contrasted against each other, the pros and cons were presented and the results were given in a comparative table.

Introduction

Machining is the process of shaping raw material, using cutting tools to obtain a workpiece of desired dimensions at prescribed properties. Machining is widely employed due to its ability for shaping objects with complicated geometries, its capacity for achieving high degrees of dimensional precision and surface tolerances, as well as its use of inventive cutting devices to enable varying types of operations. Material wastage and long running operation cycles, on the other hand, are cited as disadvantages of machining [1,2]. The fundamentals of machining lie in the removal of material from the raw workpiece to obtain the desired final shape and size. The formation of chips resulting from the cutting operation affects the surface quality of the workpiece and attributes of the chips thus formed can provide information about the resulting surface finish [3]. The dimensional properties of the chips formed during the cutting operation depend on the ductility, strength, and crystal structure of the workpiece. While increased ductility leads to continuous chips, chemical compound elements such as phosphorus (P), sulphur (S) and lead (Pb) found in the materials being worked increase the fragility of the chips formed. Chip morphology is influenced by a combination of factors such as tool features and cutting parameters [4], which all lead to varying types of chip formation. Chip formations in machining are categorized as continuous, discontinuous, and built up edge (BUE) [5]. Continuous chip formation results from machining of ductile materials at high cutting speed and low feed rate and depth of cut. As continuous chip formation contributes positively to obtaining the required surface finish, it is a favored type of formation [1,6]. While a continuous unbroken chip stream is a desired outcome in turning, it leads to hurdles in operational efficiency [6,7]. Chips that continuously accumulate without breaking from the workpiece negatively affect operator safety and tool wear [8,9]. The occurrence of chip wrapping around the workpiece damages surface quality [10]. Chip build-up in the cutting zone leads to heat accumulating on the cutting tool and the workpiece, instead of being removed [11]. Continuous chip streaming is one of the mechanisms triggering tool wear [5]. Combination of wear mechanisms and effects of heat have negative outcome on tool life [5,8,10]. Continuous chip occupying the cutting zone impedes the cutting fluid from making its way into the cutting zone. Continuous chip streaming also increases the power used in the operation [12]. Storage and transportation of chips lead to hurdles in post-machining operations as well. These undesirable outcomes involving continuous chip formation increase operational costs and lead to longer work cycles. The factors enumerated above have made chip control a priority in order to advance efficiency in machining. Chip control continues to be worked as a topic of current relevance by those in academic researches as well as by equipment and cutting tool manufacturers. Previous research indicates that for successful chip control, chip breaking must be employed. Various methods have been developed for effective chip breaking in order to eliminate the adverse outcomes. As part of this study, the aforementioned methods have been researched in depth, and

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classified under the following five headings:

1 Chip breaking effect of cutting parameters
2 Chip breaking effect of chip breakers
3 Chip breaking effect of vibration
4 Chip breaking effect of coolants
5 Chip breaking effect of specialty breaker apparatus

Experimental research has shown that hard-to-break or non-breaking chips may be addressed by modifying cutting parameters. It has been reported that feed rate and depth of cut affect chip propensity for breaking [13]. In order to obtain discontinuous chips and contribute to cutting efficiency as well as machining safety, wide use of chip breakers in various forms is reported [14]. Another technique is the use of high pressure coolants for chip breaking [15]. Chip breaking using vibration has also been studied [11]. Design of custom chip breaker apparatus as a method for chip breaking has been developed.

This paper describes the detailed research conducted into the problems resulting from continuous chip formation and the methods devised to overcome the problems in question. All of the discussed methods, as well as the corresponding studies that were conducted, have been analyzed. The advantages and disadvantages of the methods, as well as their capabilities towards solving the problems at hand, have been evaluated.

Mechanics of chip breaking

Chip formation starts with the very first curling of the chip, and is influenced thereafter by such operational parameters as cutting speed, feed rate, depth of cut, rake angle, type of material being machined, and tool geometry. Cutting parameters are effective on several chip properties, including chip color, saw-toothed patterns and formation of micro-cracks [16]. Three mechanisms are encountered for chip breaking: self-breaking, breaking upon contact with the tool, and breaking upon contact with the workpiece [17]. While self-breaking is preferred, the chip streaming direction must be properly induced for this outcome. Chip contact with the tool or the workpiece may lead to problems relating to tool wear and surface finish. Chip flow and chip curvature are significant factors in chip breaking. Chip flow is a determining factor in terms of chip breaking, as it influences both chip curve and orientation. Chip flow direction is analyzed in two groups: lateral-curl flow and up-curl flow. Three-dimensional chip flow is a composite of these two flow directions [4,18,19]. Tool properties and feed rate are the two most significant parameters affecting chip flow and curve. The bending moment due to cutting, as well as the friction in the chip-tool interface, influence the behavior of chip curvature [20]. A smaller chip curvature radius results in stronger chip breaking taking place [6].

Survey of literature indicates two primary approaches for research involving chip breakage. The first involves chip breakage through mechanical tension, and is further analyzed under two headings:

- Chip curvature analysis: These studies theoretically describe the relationship between chip curvature radius and chip breakage tension [21,22].
- Finite elements analysis: Finite elements analysis method is used to attempt to describe properties of chip breakage. [23–25] However, the results of the studies were not found to be corroborated using experiments [19].

The second approach involves the establishment of a database derived from experiments on chip breakage [26,27]. Nakayama and Li's chip breaking criterion are widely used in related research, and therefore considered in detail in this paper [18].

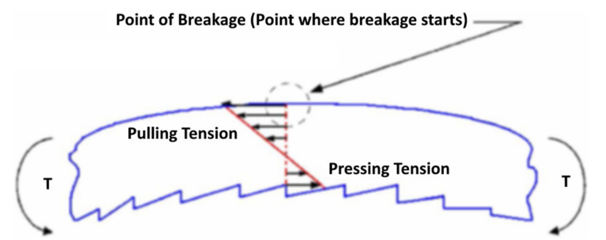

Fig. 1. Bending tension leading to chip breaking [28].

Nakayama's chip-breaking criterion

Chip breaking may be likened to torsion of a spring. Chip breaking takes place due to the tension resulting from bending. The bending experienced by the chip results in strains due to compression and tension. However, chip breaking takes place as a result of the tension formed on the outside of the chip curvature [28]. A decreasing radius of curvature increases the difference between the tensions for compression and tension; and therefore, breaking takes place in an easier fashion (Fig. 1).

It is desirable for the chip to break without getting tangled around the workpiece or the cutting tool. The critical radius of chip curvature prior to the start of any tanglement is defined as R_L. Chip formation starts with a curvature radius of R_0. Given chip surface strain (ε) and chip endurance strain (ε_B), if the surface strain is greater than the endurance tension ($\varepsilon > \varepsilon_B$), it is expressed that chip breaking will follow. It is noted that chip flow takes place with an up-curl radius of R_0 and that this flow is consequently blocked by the workpiece surface and the cutting tool [21].

$$\varepsilon_B = \frac{t_2}{2}\left[\frac{1}{R_0} - \frac{1}{R_L}\right] \quad (1)$$

In Eq. (1), t_2 denotes chip thickness. R_0 is the chip curvature radius, while R_L is the critical radius value relating to chip tanglement (Fig. 2).

Li's chip-breaking criterion

Li proposed a semi-empirical chip breakage model based on Nakayama's research and the associated theory of chip breakage limits [22]. The model uses critical feed rate and depth of cut theory for chip breakage. According to the theory, chip breakage occurs when depth of cut (d) is larger than the critical depth of cut (d_{cr}), and feed rate (f) is larger than the critical feed rate (f_{cr}). The corresponding Eqs. (2) through (5) governing f_{cr} and d_{cr} are shown below:

$$f_{cr} = \frac{\varepsilon}{\left(\alpha(1/R_0 - 1/R_L)\frac{\sin\kappa_\gamma}{C_h}\right)} \quad (2)$$

$$d_{cr} = \left(\cos\frac{57.3\varepsilon_B\rho\cos\delta}{\alpha r_e}\right) - r_e \Rightarrow d < r_e \quad (3a)$$

$$d_{cr} = \frac{\varepsilon_B\rho\cos\delta}{\alpha} - \left(\frac{\pi}{2} - 1\right)r_e \Rightarrow d \geq r_e \quad (3b)$$

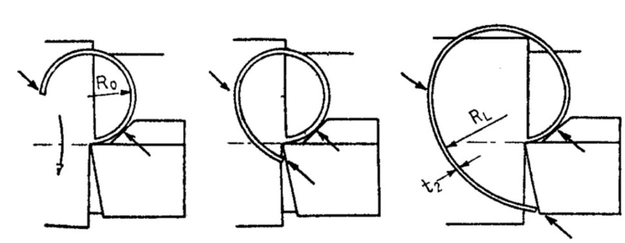

Fig. 2. Chip formation and critical chip dimensions [21].

In Eq. (2), K_γ is the cutting edge angle, C_h is the cutting ratio, and α is the cross-section shape coefficient. In Eqs. (3a) and (3b), ρ is the radius of side-curl chips, δ is a chip cross-section related parameter and r_e is the insert nose radius [18].

However, the values d_{cr} and f_{cr} cannot be used to predict chip breakage limits, which are influenced by several factors, with workpiece material, cutting speed and features of the cutting tool being of primary importance [22]. Taking into account these concerns, Li developed Eqs. (4) and (5) shown below, corresponding to f_{cr} and d_{cr} respectively:

$$f_{cr} = f_0 K_{fT} K_{fv} K_{fm} \quad (4)$$

$$d_{cr} = d_0 K_{dT} K_{dv} K_{dm} \quad (5)$$

where f_0 and d_0 are standard critical feed rate and depth of cut, K_{fT} and K_{dT} are the cutting tool effect coefficients, K_{fV} and K_{dV} are cutting speed effect coefficients; cutting speed effect coefficients, and K_{fm} and K_{dm} are the workpiece material effect coefficients. These coefficients were determined through machining tests. The coefficients may be calculated based on cutting conditions and chip breakage capability may be predicted for specific cutting conditions.

Chip breaking methods

Chip control is essential for high efficiency and reliable machining. To eliminate the negative effects of the formation of continuous chips, chips must be broken and removed from the cutting zone. Chip breaking has been studied extensively and various methods have been devised based on the studies.

The effects of cutting parameters on chip breaking

Cutting parameters directly affect chip formation, as well as chip shape and dimensions. Depth of cut and feed rate are factors of special importance in terms of chip breaking. Increasing the values of these parameters increases chip tendency for curling and breaking [12]. Increased feed rate decreases chip curvature radius, leading to increased chip fragility. An increased depth of cut, on the other hand, leads to a higher compression effect. Due to the increased pressure it produces, higher compression results in decreased cutting resistance, whereby the stress values necessary for chip breaking are more easily achieved [13]. For testing the breaking of continuous chips formed during the turning of AISI 304 stainless steel, experiments have been conducted using three separate values for cutting speed, feed rate, and depth of cut. The results of the study indicate that as feed rate and depth of cut values are increased, the tendency for chip breaking is increased and chip breaking is observed [29]. For testing chip breaking and surface finish during the turning of AISI 4140 stainless steel, experiments have been conducted using three separate tools and feed rates and two separate depth of cut values; results indicate continuous chip formation with tanglement at lower feed rates, and distinct chip breaking observed at increased feed rate values [10].

Development of an algorithm was planned to discover the relationship between cutting parameters and chip form, and to control cutting parameters. Towards this goal, turning experiments were conducted using two types of cutting inserts made from AISI 416 martensitic stainless steel of types SM and MF. Chip forms and forces were evaluated. Increased chip fragility was observed for both cutting inserts, along with increases in feed rate and depth of cut.

Along with increased feed rate, chip accumulation in the chip breaker groove was observed, leading to increases in chip contact as well as more effective chip breakage. Increased feed rates led to increased performance of the chip breakers [30] (Fig. 4).

In experiment for chip control employing the hard turning of type AISI 1045 hardened-steel, three cutting speeds (110 m/min, 193 m/min and 276 m/min), three depths of cut (0.1 mm, 0.2 mm, and 0.3 mm) and three feed rates (0.05 mm/rev, 0.1 mm/rev and 0.15 mm/rev) were used. Two cutting speeds (414 m/min and 512 m/min) were selected for use in the verification experiments. Experiments were conducted using cutting tools with the SV chip breaker form. Cutting forces, surface roughness and chip morphology were analyzed. It was determined that low cutting speeds led to continuous chip formation and that boosting the cutting speed increased the tendency for chip breakage. Chips with a saw-toothed morphology were observed to be produced at high cutting speeds, with chips breaking more easily due to the curvature induced by the chip breaker geometry [31].

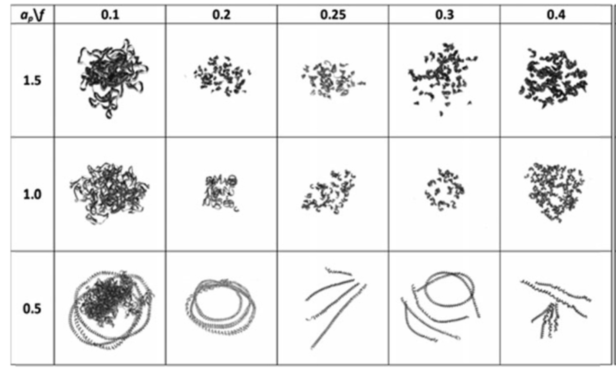

Fig. 3. Various chip formations corresponding to differing cutting parameters; chip breaker type MF, V_c = 240 m/min [30].

Literature survey reveals that chip breaking takes place more easily at increasing feed rates, cutting speed and depths of cut (Fig. 3). However, the increase in feed rates and depths of cut have a negative effect on surface quality of workpiece, tool life and cutting forces.

The type of material being machined is significant in determining the parameters for cutting. Improperly selected cutting parameters lead to a negative outcome in terms of tool life. Additionally, higher values for feed rate and depth of cut result in decreased surface quality [12,29]. Furthermore, in case of the machining of certain types of materials, modification of cutting parameters are shown to be ineffective in the amount of chip removed. The chip breaking effect of cutting parameters are shown in Table 1.

Chip breaking effect of chip breakers

Chip breakers in various forms are widely used in machining to break long, continuous, and stringy chips. A chip breaker is either an obstruction-type device attached to the tool-chip interface that acts to inhibit chip flow, or a groove-type device, with grooves of varying geometric shapes, found on the tool surface. Chip breakers improve chip breakability by reducing chip curl radius, leading to more effective chip control [9]. The groove-type breakers result in reduced surface contact between tool and chip. Thus, by facilitating temperature reduction in the tool-chip interface and reducing power requirements, as well as improving surface finish of the machined part, chip breakers provide several benefits [8]. A coated cutting insert having groove type chip breaker was used to reduce contact between tool and chip and facilitate chip breakage in turning of 18MND5 mild steel. The machining process was evaluated by cutting force and chip morphology and the results depicted that there were contact discontinuities between the cutting insert and chip interface. The reduced contact area facilitated the chip flow and semi-continuous broken chips were obtained due to the cutting tool geometry during the rough turning process [32]. A model has been developed whereby the effects of cutting parameters are used to determine chip breaker dimensions. It has been determined that chip breaker dimensions have an effect on chip curl radius. In the following discussion, the symbols and their meanings are as follows [33]: (Fig. 5)

R_c:chip curl radius

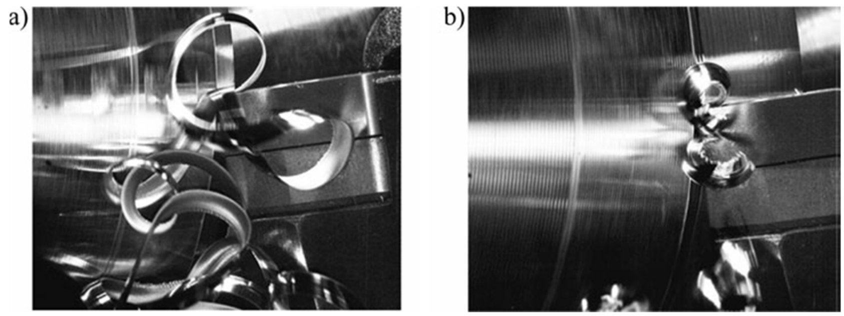

Fig. 4. Examples of chip formations for chip breaker type SM, V_c = 240 m/min and ap = 1.5 mm; a) unacceptable chip formation at f = 0.1 mm/rev., and b) ideal chip formation at f = 0.3 mm/rev. [30].

W:chip breaker width, measured along tool surface
l_c:length of tool-chip contact
h:height of chip breaker groove
γn:chip breaker angle
W_n :chip breaker width
Eq. (6) describes chip curl radius in relation to tool geometry:

$$R_c = \frac{(W - l_c)^2}{2\mathrm{h}} + \frac{h}{2} \tag{6}$$

The parameters *W* and *h*, which determine chip breaker dimensions, are denoted by Eqs. (7) and (8):

$$W = W_n cos\gamma_n \tag{7}$$

$$h = W_n sin\gamma_n \tag{8}$$

When Eq. (6) is revised using Eqs. (7) and (8), it is transformed into Eq. (9) as shown below:

$$R_c = \frac{W_n}{2\mathrm{sin}\gamma_n}\left[1 - 2\frac{l_c}{W_n}cos\gamma_n + \frac{l_c^2}{W_n^2}\right] \tag{9}$$

Several studies have been conducted to reveal the effectiveness of chip breakers. Properties of chip breaking have been tackled at both analytical and experimental fashion. As part of the study, a new parameter (C_B) was developed denoting chip breaking index, based on chip thickness and length. Eq. (10) was derived through a series of equations based on the moment created from chip contact with the workpiece:

$$\frac{t_c}{l_c} = \frac{6kF_u}{\sigma_f} \tag{10}$$

In Eq. (10), t_c denotes chip thickness, l_c denotes length of chip segments after chip breaking, F_u is the reaction force per unit area and σ_f is the chip breaking tension. The left hand side of Eq. (11) is defined as the chip breaking index.

$$C_B = \frac{t_c}{l_c} \tag{11}$$

As part of the experiments conducted, two types of material (SM45C, SS41) and three types of cutting tools (KA, KC, MG) have been used. Two cutting speeds (100 m/min and 200 m/min) and three depths of cut (1 mm, 2 mm, 3 mm) have been employed. Chip breaker geometries have been tested under six different feed rates (0.067, 0.111, 0.148, 0.234, 0.296, 0.345 mm/rev). Increases in feed rate have been observed by using, for the KC-type breaker, two additional feed rates (0.444 and 0.542 mm/rev), and for the MG-type breaker, three additional feed rates (0.444, 0.542 and 0.641 mm/rev) (Fig. 6).

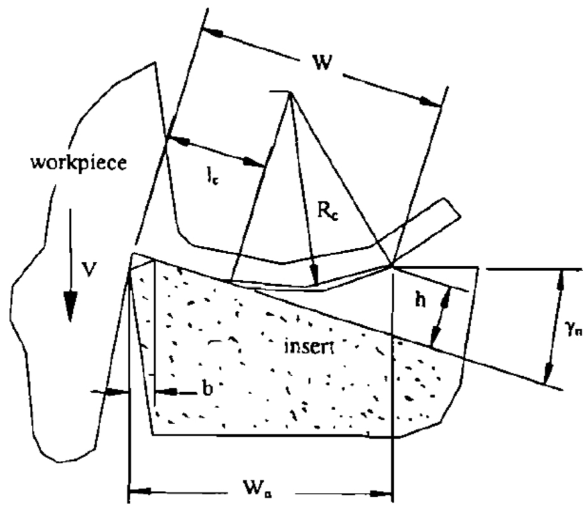

Fig. 5. Chip breaker cross-section and chip formation [33].

As a result of the experiments, chip breaking was observed in response to increase in feed rate, and chip shape was observed to change from “6” and “9” shapes, to the “C” shape. The study results determined that C_B values in the range of 0.05 to 0.2 formed somewhat broken chips, while increasing C_B values resulted in higher chip fragility [34] (Fig. 7).

Using chip breakage ratio, chip breaking properties were attempted to be explained through a hybrid model resembling chip breakage index. The model has revealed the “chip breakage ratio (ζ)”, calculated as the ratio of chip radius (R_L) vs starting chip radius (R_O), shown in Eq. (12).

Table 1
Chip breaking effect of cutting parameters.

	Level					
Effect	5	4	3	2	1	Description
Environmental			X			No environmental effect (positive or negative) observed.
Chip breaking		X				Effective breaking on ductile materials not achieved.
Machinability					X	Increases in surface roughness, cutting forces and tool wear.
Applicability	X					Ease of configuration of cutting parameters on equipment.
Cost				X		May increase energy and tool costs based on effects of machinability.

5: Positive **4**: Partially positive **3**: No effect **2**: Partially negative **1**: Negative.

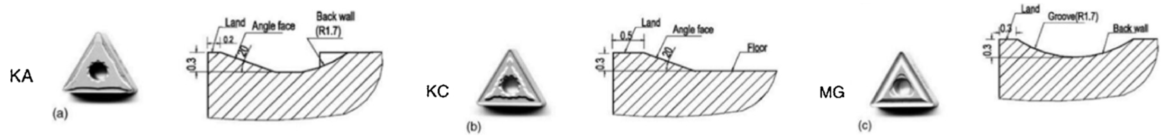

Fig. 6. Chip breaker geometries: a) KA, b) KC and c) MG [34].

$$\zeta = \frac{R_L}{R_0} \tag{12}$$

Chip radius was measured using microscope, and starting chip radius was calculated theoretically. The experiments were carried out using four types of chip breaker geometry (CG, CM, DM and PM), three cutting speeds (100, 200 and 300 m/min), five feed rates (0.08, 0.16, 0.24, 0.32 and 0.40 mm/rev), and three depths of cut (1, 2.5 and 4 mm). The calculated chip breakage ratios were classified into three: usable, acceptable, and not acceptable. The classification "usable" is for values where $\zeta < 1$; "acceptable" for values where $1 \leq \zeta \leq 2$; and "not acceptable" for values where $\zeta > 2$. Through testing, the model was verified against a fifth type of chip breaker geometry (W). Consequently, the model was observed to produce successful predictions. It was stated that the chip breakage ratio values fell below 1 as feed rate increased, thus leading to useable chip formation [35]. In addition to studies on the modeling of chip breakage mechanisms, research was also conducted on the modelling of the geometrical properties of chip breaker grooves. Regression analysis was used following empirical and experimental studies, and models were developed. It was stated that the aforementioned models may assist in determining chip breaker geometries [36].

Asymmetrical (AGT) and symmetrical (SGT) chip breaker grooves have been compared under dry conditions, using five different depths of cut and feed rates, and at 110 m/min cutting speed (Fig. 8).

The results indicate that the AGT-type chip breaker performs better in comparison to the SGT-type chip breaker. It was observed that at minimum depths of cut, the width of the chip breaker groove influences the results, while at minimum feed rates, groove width, groove depth, and groove back wall height influence the results [37] (Fig. 9).

Geometric parameters relating to chip breaker groove (groove depth, width, starting distance, and base radius) have been interpreted using artificial neural networks, based on the results of experiments involving SCM4 (AISI4140) type material, using thirteen types of cutting tools designed for various operational purposes, at seven depths of cut and three feed rates. It was determined that for chip breaking, chip breaker groove depth and width have significant influence on the results. It was determined that with increasing groove depth and decreasing groove width, chip breaking performance improved for finishing cuts, and that with decreasing groove depth and increasing groove width, chip breaking performance improved for rough machining. It was expressed that through the use of the artificial neural networks developed, determining chip breaker geometries will become easier and costs will be reduced [38] (Fig. 10).

In addition to having grooves on the tool inserts, it was proposed that bulges may also be employed on tool surfaces, and such a bulge was formed on an HSS lathe tool using laser powder coating; subsequently, experiments were conducted to determine its chip breaking capabilities. Equations have been derived for effective positioning of the bulge on the tool surface. A workpiece made of aluminum alloy AlCu4Mgl was used in the experiments. As cutting parameters, a constant cutting speed of 100 m/min at two feed rates and depths of cut were employed. The bulge was found to have a positive effect on chip breaking and the derived equations were observed to be in line with the results of the experiments [39] (Fig. 11).

In addition to the performance implications of the chip breaker geometry, its effects on machinability parameters were also researched. The tests were conducted using both dry and wet machining, with 20 mm constant cutting length, 150 m/min cutting speed, 0.16 mm/rev feed rate and 1 mm depth of cut. Grooves were machined into the cutting tool at different angles, and cutting performance was analyzed using AISI 316 austenitic-type stainless steel material. Two types of tools were compared for effects on cutting force performance and tool wear in turning: tools with grooves 1) parallel and 2) perpendicular, to chip flow direction, as well as conventional tools. It was discovered that under all conditions, the grooves resulted in lower forces being

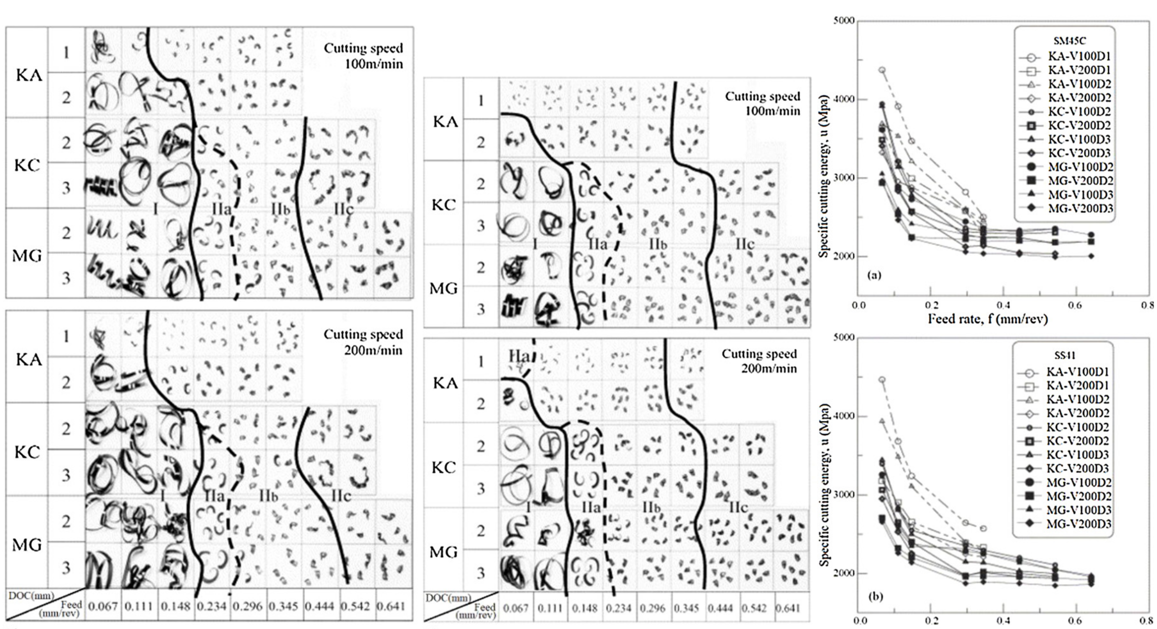

Fig. 7. Chip formations and chip break index [34].

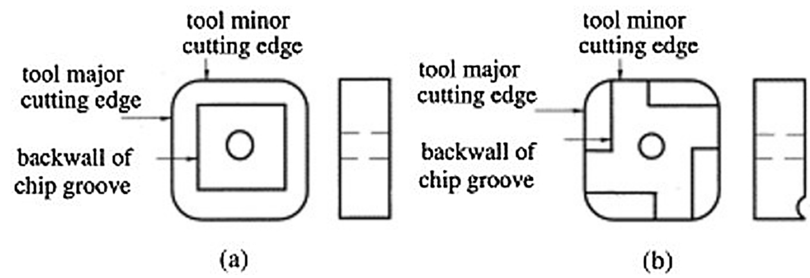

Fig. 8. Chip breaker shapes: a) SGT-type, b) AGT-type [25].

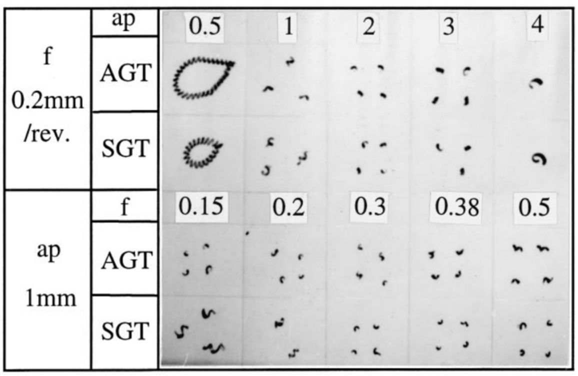

Fig. 9. Comparison of chip breaking using asymmetrical and symmetrical chip breakers [37].

observed, reduction of chip clinging, and more effective lubrication performance under wet conditions [40] (Fig. 12).

A simulation was developed for the turning operation and tests were conducted to verify the validity of the simulation results. In tests employing various chip breaker geometries and using AISI 1045-type steel material, the variance in cutting forces and chip formations were analyzed. In the study, five different cutting tools were used, one with a chip breaker and the other four tools without. Results indicate that cutting forces are affected by chip breaker geometry and that test results are in line with output obtained from the simulations. It was reported that, among the geometries studied, the CG-type chip breaker proved to have superior performance with respect to lower cutting forces required and the formations of the chips produced [41] (Fig. 13).

The effects of different cutting edges, chip breaker forms, and cutting parameters on the forces were observed and surface roughness were analyzed. Three separate chip breaker forms (MR, MM, QM), cutting speed, feed rate, and two depths of cut have been employed. The tools had identical attributes but featured different geometries. The lowest force and surface quality were observed with the use of the QM-type chip breaker. The highest values were observed with the use of the MR-type chip breaker. In terms of the cutting edges used as part of the tools employed in the tests, the largest chip angle and the smallest cutting tool-chip contact point were observed with the use of the QM-type tool, which in turn affected the observed force and surface quality [8,42] (Fig. 14).

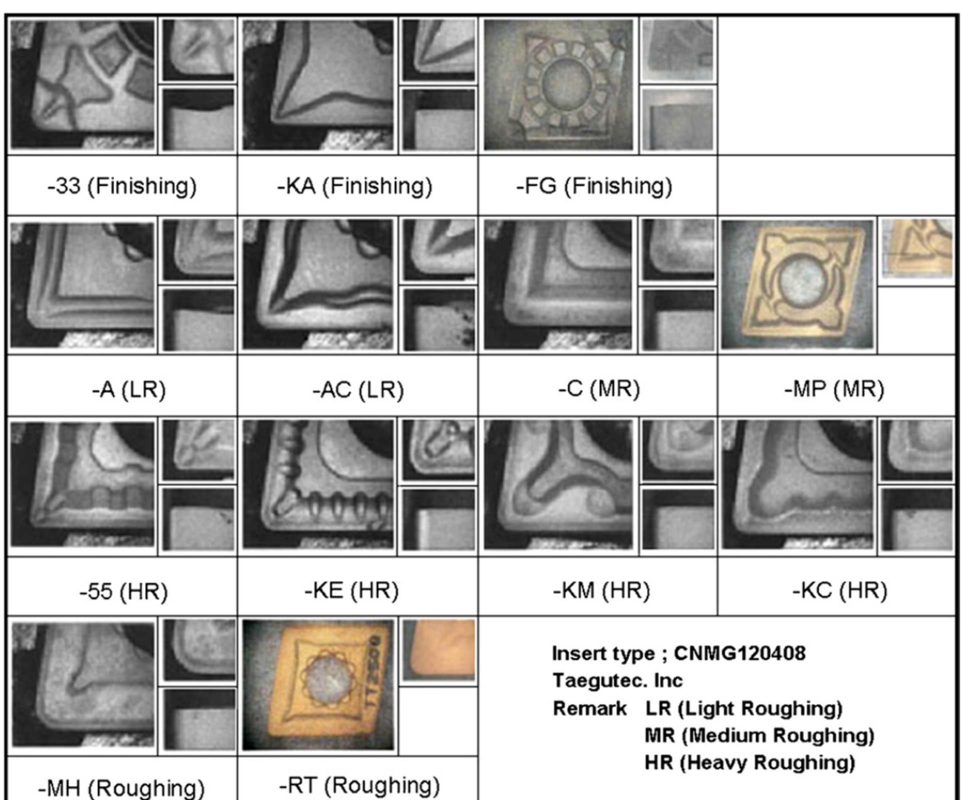

Fig. 10. Cutting tools and corresponding chip breaker geometries [38].

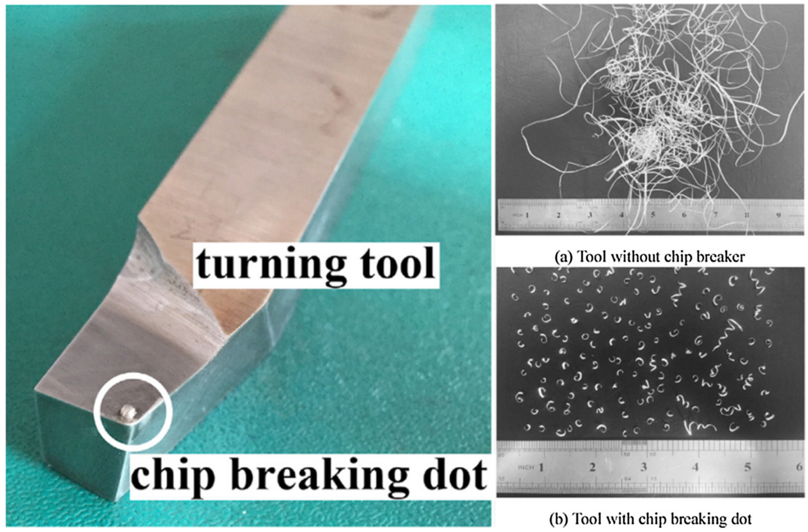

Fig. 11. Chip breaking dot employed by an HSS tool and its effect on chip breaking [39].

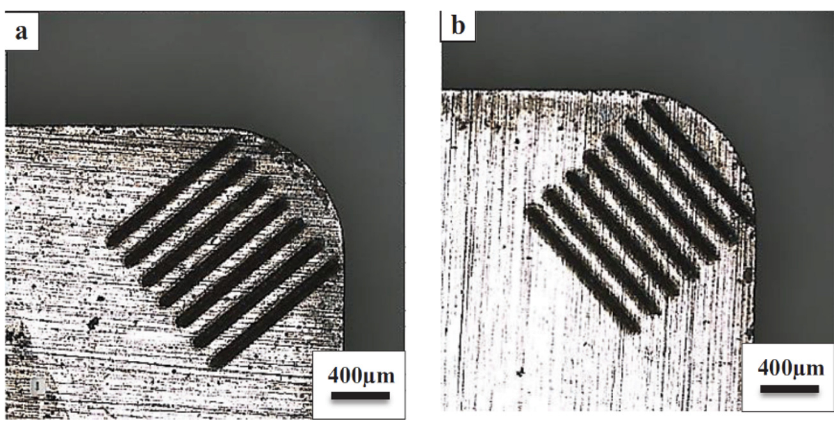

Fig. 12. Optical images of tools with micro-grooves: a) In-line with chip flow, b) perpendicular to chip flow [40].

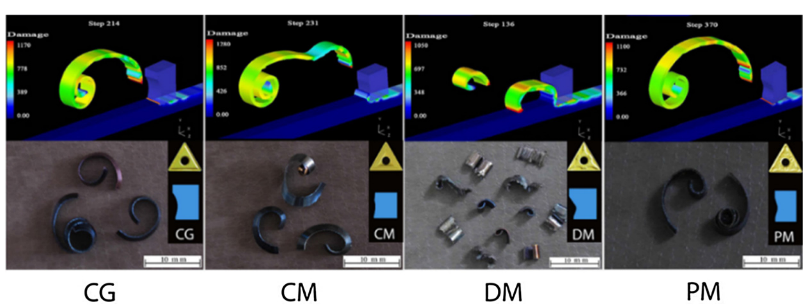

Fig. 13. Simulation of chip forms and experimental results [41].

Reduced forces and increased surface quality have improved cutting efficiency [9]. The effects of various chip breaker geometries on surface finish were studied and the test results were modeled using artificial neural networks. It was reported [43] through studies that in general, the highest surface roughness was observed with the use of the MA-type chip breaker, and that the lowest levels of surface roughness were observed with the use of the MS and SA-type chip breaker forms. Studies have also been conducted on the effects of chip breaker geometries on

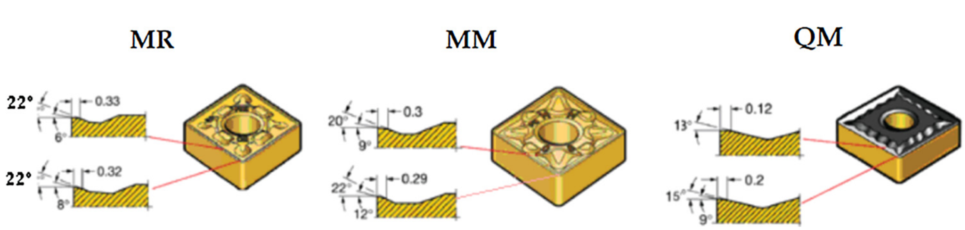

Fig. 14. Attributes of the tools used in the tests [8].

forces, and lathe turning tests were carried out using AISI 1050 steel material employing chip breaker equipped tools with and without coated tools. The results indicate that with an increase in the chip breaker geometry, observed forces increased as well. Estimation of the forces generated was targeted by the study, based on a forecasting model developed using the length of the chip breaker geometry and associated angles. The model thus created was observed to produce successful results [44,45]. Effects of chip breaker geometries on the stress forces they impose on the cutting tool were studied as well. Five types of chip breaker geometry (SA, MA, GH, MS, STD) were compared in experiments that measured cutting forces and corresponding stress formation on the tool. The highest cutting force was stated to be observed on the SA type breaker. Highest stress formations were observed for SA and MA type breakers, while the STD type breaker showed the lowest level of stress formation [46]. Optimization efforts were carried out towards achieving efficiencies in machinability through chip breaker geometry selection. Finite elements method was utilized in the analysis of chip breaker parameters [47,48]. Optimum values were determined for the h1, h2 and W breaker dimensions used in Fe-Cr-Ni type stainless steel. Chip curvature radius (r), chip thickness (a_{ch}), tool stress (σ), temperature (T) and cutting force (F) were considered in the optimization of chip breaker parameters. Cutting forces were calculated using the developed model, and compared with the values measured in the experimental studies that were conducted; consequently, success of the model was confirmed. Cutting forces (F), chip curvature radius (r) and chip thickness (a_{ch}) were not meaningfully affected by increasing h1 and h2 values. Temperature (T) increased with an increase in h1, but did not show a meaningful change with an increase in h2. Tool stress (σ) decreased with increasing h1; with an increasing h2, tool stress increased initially, but then showed a tendency to decrease. The optimal value was determined as 1 mm for W, and 0.15 mm for h1. It was advised that smaller h2 values be preferred for low cutting speed and high feed rate, and larger h2 values be used for high cutting speed and low feed rate [48].

It was also observed that chip breaker geometry favorably affected parameters related to machinability. In fact, this effect has even led to the use of chip breaker forms in milling operations where continuous chip formation is not encountered. Forming chip breaker geometries on available milling cutters was studied. Various chip breaker geometries were determined using finite elements analysis. The ideal breaker geometry was applied on to the tool using laser etching operations. Milling cutters with and without chip breakers were used in the machining of A356 type aluminum alloy and the results were compared. It was determined that chip breaker geometries did not affect cutting forces; their use increased chip curvature and significantly improved surface roughness [49]. In tests where AISI 316 stainless steel material was put through milling, three different forms of chip breakers (ERGP, SRGC, ERGC), cutting speed, and feed rate were used. The effects of varying cutting parameters and chip breaker forms on tool wear and surface roughness were studied. It was reported that the use of the ERGC-type chip breaker limits the length of the contact between tool and chip, thereby leading to faster chip removal and in turn, reduced heat buildup in the cutting zone. It was expressed that therefore, tool wear was delayed and tool life was extended. In terms of surface quality, it was observed that the ERGC-type chip breaker again provided better overall results [50] (Fig. 15).

Turning is the primary machining operation where continuous chip formation is cited as a problem. Continuous chip formation is also cited as a problem in drilling of holes. Chip formation traps heat in the cutting zone, leading to problems with chip removal, chip entanglement and tool breakdown. To mitigate these problems, it was suggested in one study to decrease drilling force, provide for an improved drill performance and machining of a groove onto the drill bit surface for chip breaking purposes, in order to facilitate chip breaking and thereby achieve chip control. AISI 1080 steel material was used in the tests, and parameters were varied with respect to number of revolutions, feed rate, groove angle, groove width, and groove depth. Each variable was configured to have two values in the tests. The groove that was cut into the drill bit was found to be effective in chip breaking, reducing the forces involved, increasing the critical drilling depth value, and improving overall tool performance [51] (Fig. 16).

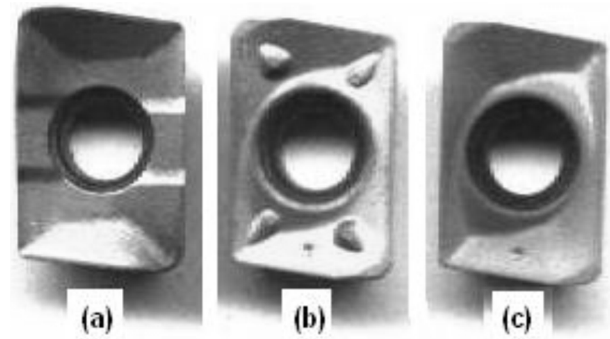

Fig. 15. Chip breaker geometries: a) ERGP, b) SRGC, c) ERGC [50].

The effectiveness of the groove machined onto the drill bit was analyzed in another study and an equation was devised for groove placement on various drills. Standard and parabolic grooves in drills with two different diameter values were evaluated using AISI 1018 material. Results indicated that chip dimensions showed decreases with the use of both groove geometries with parabolic grooves producing smaller chip formations [52]. The effects of drill geometries on cutting parameters and chip formations were analyzed using four sub-categories of values as control parameters for drill geometry, cutting speed, and feed rate. The study used spheroidal graphite cast iron. Tool geometries 1 and 2, shown in Fig. 17, are widely used in industry, while tool geometries 3 and 4 show drill bits specifically designed for the study. The study results indicate chip breakability increasing with feed rate, with the smallest chip formations being observed with the use of the custom tool geometries 3 and 4 [53]. However, it is not enough to emphasize only the influence of cutting variables on the drilling process. At this point, the quantitative evaluation appears to be necessary to emphasize the effect of cutting parameters on the machining process. Chip size has an effect on chip evacuation and broken chips can be removed easily from the machining area with a low-pressure coolant. Therefore, measuring the size of the chips using the appropriate parameters should help in selecting the most suitable cutting parameters improving the cutting performance. The chip break depends on the amount of undeformed chip thickness ($t1$) and Chip Fragmentation Ratio (CFR) was presented as a new parameter during the deep hole drilling process of the 18MND5 steel. The CFR is the ratio of the chip length to non-deformed chip thickness ($t1$).

$$CFR = \frac{l}{t1} \tag{13}$$

The quantitative analysis indicated that the cutting speed has a minimum effect on the length of the chips. On the other hand, it was observed that the ratio of chip breaking and productivity were increased with increasing feed rate. However, the upper limit of feed rate and cutting speed values must be set correctly to avoid excessive flank wear and crater wear, respectively [54].

As mentioned earlier, chip breaker geometries are the primary and widely used chip breaking methods, due to the advantages they provide and the positive effects they have on the parameters used for machining. However, despite these benefits, development of a new tool with chip breaking capabilities require molding, sintering, grinding, and coating, as well as various tests for evaluation, leading to efforts involving high costs [9,38]. At the same time, some cutting tools with chip breakers have been reported to underperform in terms of chip breaking when machining certain ductile materials [12,55]. The chip breaking effect of breaking methods are shown in Table 2.

Fig. 16. Groove cut into drill bit and its effect on chip breaking [51].

Chip breaking through vibration

Continuous chip formation poses a problem when machining such materials as superalloys, titanium, and aluminum, which are all used primarily in the aviation industry. In these cases, chip breakers have fallen short of expectations. One solution developed towards addressing the issue was to use vibration frequencies for chip breaking. Studies on the use of vibration for cutting have been ongoing for some time. Since 1950, the effects of vibration on chip formation have been researched [56]. In a related study, chip breaking using low frequency vibrations have been examined. A CNC application was used in creating the vibration frequency. In the study, the vibration motion was utilized in two directions; namely, in the cutting direction and in the feed direction. It was stated that the vibration motion should be proportional to number of revolutions, and the vibration amplitude should be proportional to the feed rate. The study results indicate that, with respect to chip breaking, it is preferable to apply the vibration in the direction of the feed rate. It was stated that the study results may be applied to hole drilling operations [11]. With the use of a method named MAM (Modulated Assisted Machining), chip control in CBN tools and CGI materials was targeted. Using low frequency vibrations, chip breaking was achieved by limiting the contact between the tool and chip. Among the benefits of the system, advanced chip control, reduced tool wear, and a higher chip removal rate have been cited. Additionally, the energy required for cutting operations was reported to be reduced. The method is reported to be suitable for application in lathe operations and hole drilling [57,58] (Fig. 18).

The chip formation resulting from AISI 304 stainless steel machine-turned using LFV (Low Frequency Vibration) and its effect on cutting forces was analyzed. Constant cutting speed of 3752 rev/min and four different feed rates (0.005, 0.01, 0.02, 0.03) were employed in the experimental study. Vibration frequency of 93.8 Hz for chip breaking was used, with a 1.5 ratio of vibration amplitude to feed rate. Evaluation of the data showed reduction in average forces in LFV compared to conventional machining, with increases in maximum force values. It was expressed that chip breaking resulted in reduction being observed in average forces; vibration motion and feeding motion were combined, and at the maximum feed rate, the highest values were

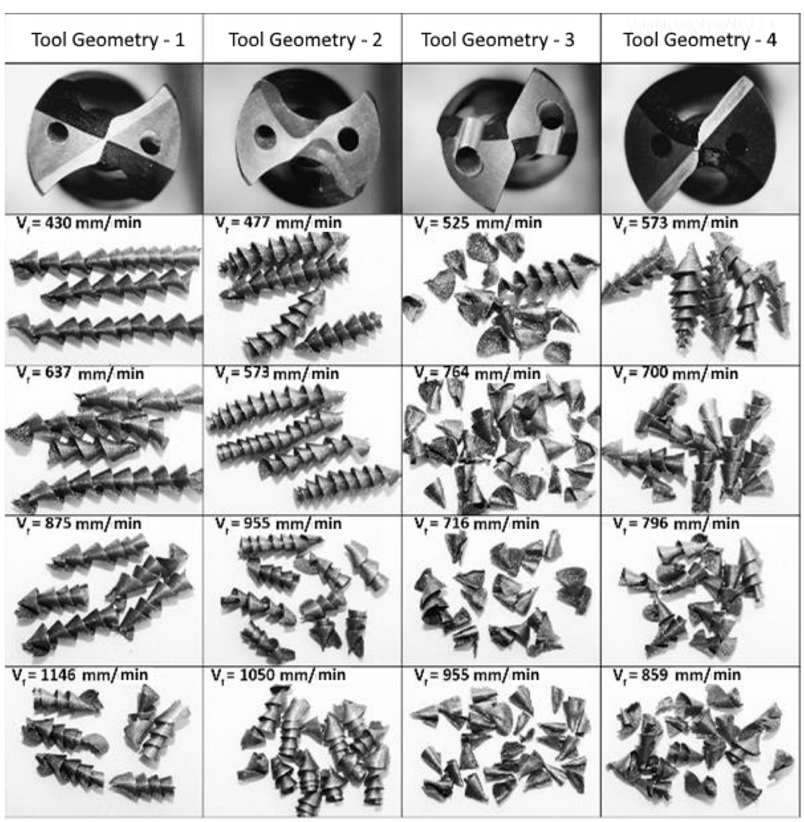

Fig. 17. Chips formations corresponding to varying tool geometries [53].

Table 2
Chip breaking effect of breaking methods.

Level						
Effect	5	4	3	2	1	Description
Environmental			X			No direct environmental effect observed.
Chip breaking		X				Chip breaking on ductile materials not achieved.
Machinability	X					Surface roughness improved, cutting forces reduced.
Applicability	X					Tools with chip breakers are readily available for procurement.
Cost				X		May increase tool costs due to the required additional operations.

5: Positive **4**: Partially positive **3**: No effect **2**: Partially negative **1**: Negative.

observed corresponding to forces involved. The desired chip breaking was achieved using the aforementioned method. The necessary vibration was realized through the use of the tool servo motors [59] (Fig. 19).

A group of researchers developed a model for the LFV operations they used in the past. The developed model geometrically describes chip breaking conditions. Accordingly, it was the goal of the study to determine ahead of time the properties of the vibration necessary for chip breaking. AISI 304-type stainless steel was used in the study [60] (Fig. 20).

In a study examining the changes in temperature and surface quality with vibration in the direction of feed rate, lower temperature values compared to conventional machining were reported due to less contact as a consequence of vibration, and which in turn reduced tool wear. In these studies, where the goal was to achieve acceptable surface roughness values using vibration in chip breaking, determining the surface roughness ahead of time was stated as a goal and a simulation was developed, accordingly. Tests were run to verify the developed simulation, where a constant revolution per minute of 300 rpm and feed rate of 0.0635 mm/rev were used. The workpiece was made of Aluminum 6061 material. The effects of variable frequency and amplitude values were examined. While surface quality was found to be acceptable for those conditions leading to chip breaking, certain surface regions were found to have adverse surface roughness values. It was stated that through the use of the developed simulation, surface roughness can be forecast to a reasonable degree [61–63]. Turning tests were conducted on Inconel 718-type material using ultrasonic vibration cutting (UVC) operations. The tests were conducted using a cutting depth of 0.1 mm, vibration frequency of 19 kHz, 15 mm of vibration amplitude, four feed rates in the range of 0.025 mm/rev through 0.1 mm/rev, and six cutting speed values varying between 5 m/min and 20 m/min. During the UVC cutting operations, it was determined that the parameters for tool vibration amplitude, tool vibration frequency, feed rate, and cutting speed significantly affected tool-workpiece contact ratio (TWCR) and tool-workpiece contact speed (TWRS). The study examined the effects resulting from varying cutting speed and feed rates under constant frequency and amplitude on cutting forces, tool wear, and surface quality. It was reported that UVC prolonged tool life through reduced cutting speed that it partially improved surface quality and that it reduced the forces involved. It was stated that this was caused by reduced TWCR due to lower cutting speeds. Increasing cutting speed led to the formation of impact cutting conditions, leading to increased wear values. It was stated that UVC is efficient in lower cutting speeds, but that it proved to be lacking in chip breaking under such cutting conditions [64]. Turning tests on Ti-6Al-4 V type material using very low frequency vibration were conducted and the effects of vibration on forces, tool wear, and cutting performance were examined. Results have indicated that crater wear and average forces showed reduction due to vibration and that cutting performance increased [65]. It was observed that successful chip breaking using vibration was realized. However, in cases where the appropriate vibration frequencies were generated through the tool, the effects on tool bearings and servo motors must be evaluated. The requirement for a CAM (Computer Aided Manufacturing) module matching the CNC tool for proper generation of vibrations is a significant factor involved in the effort [11]. Additionally, the vibration generated during the cutting operation is of a level that will adversely affect surface quality. While chip breaking using vibration has been in use for some time, its effects on conical and curved turning operations has not yet been researched and no fundamental solution has been put forth for chip control [60]. The effects of chip breaking using the vibration method are shown in Table 3.

Chip breaking effect of coolants

A significant portion of the heat generated during machining operations is removed through chip formation. The high temperatures observed during cutting undoubtedly reduce tool life. Therefore, it is a widely employed practice to use coolants in machining operations [66]. In machining, coolants and lubricants improve machinability, reduce tool wear, and prolong tool life; therefore, they lead to increased efficiencies in machinability. Furthermore, it is known that cutting fluids reduce cutting forces and vibration, improve surface quality and thereby have a positive influence on the overall operation [67]. In addition, coolants enable rapid cooling down of high temperature chips and contribute to their embrittlement. The use of coolants, delivered to the cutting zone at specific pressures, is an alternative solution to the problem of chip breaking. Studies have been conducted where the effects of high pressure coolants on chip breaking were investigated. Tool life, tool wear, cutting forces, surface quality, and chip morphology were analyzed in the machining of Inconel 718-type material. In the

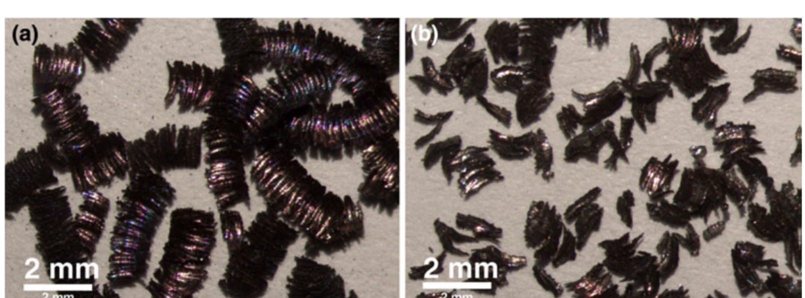

Fig. 18. Chips formations; a) using conventional machining, b) using MAM.

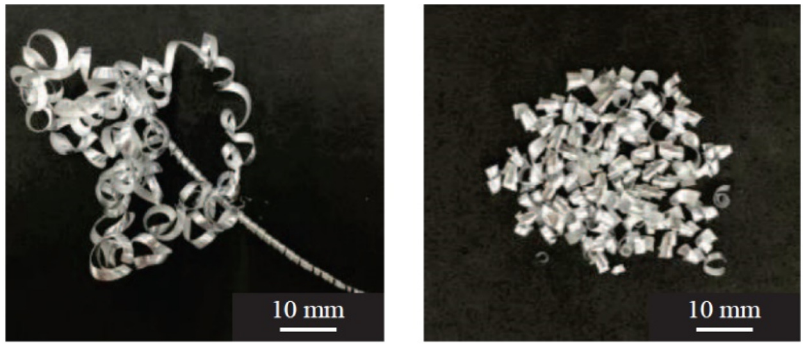

Fig. 19. Difference in chips formations; left, using conventional machining; right, using low frequency vibrations [59].

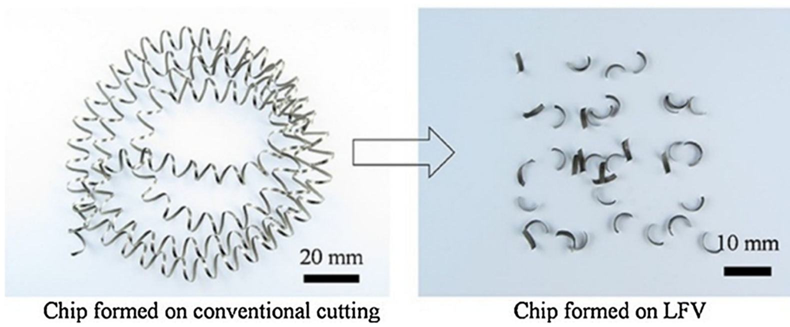

Fig. 20. Effects of LFV on chip breaking [60].

study, three cutting speeds (20 m/min, 30 m/min, and 50 m/min), three coolant pressures (110 bar, 150 bar, and 203 bar), two feed rates (0.25 mm/rev and 0.30 mm/rev), and two cutting depths (2.5 mm and 3.00 mm) were used. The study results indicate that surface quality and tool life improved with the use of high pressure coolants and the heat and force values involved in cutting were reduced. In addition to coolant pressure, cutting depth and feed rate were found to also be effective in chip breaking. In operational tests conducted at 150 bar pressure, it was observed that long and spiral-shaped chip formations were observed, that chip breaking did not take place in the 150 bar–203 bar range, while breaking did take place at the 203 bar pressure value [68] (Fig. 21).

Machinability of Inconel 718-type material was again analyzed in a similar study; tool wear, cutting forces, and surface quality were studied at a fixed cutting depth of 0.50 mm with four coolant pressure settings (11 MPa, 15 MPa, 20 MPa and 20.3 MPa) while using a tool with a ceramic insert. The study results indicate that chip breaking only took place at the 20.3 MPa pressure setting. The chip formations under conventional cooling and high pressure cooling were compared [69] (Fig. 22).

Tool wear and chip formation were analyzed in the turning of Ti-6Al-4 V type material under high pressure, and the effects of nozzle diameter, nozzle inclination angle, nozzle distance, and coolant pressure were studied. It is stated that chip dimensions decreased with respect to increasing coolant pressure, and chip breakability increased with respect to increasing nozzle inclination angle [70]. In another study employing Ti-6Al-4 V type material, high pressure coolant use was found to lead to prolonged tool life, improved surface quality, and chips broken at smaller dimensions [71]. It was established that in the turning of Ti-6Al-4 V type material, the use of high pressure coolant and lubrication leads to increased cutting forces and heat values, and improves chip breakability and machining performance. At the same time, it was observed that chip breaking did not take place under low pressure values [72] (Fig. 23).

Operations with conventional machining and turning using high pressure coolants were compared and the effects of the use of high pressure coolants on tool performance and cutting forces were analyzed. Turning tests were conducted using coated carbide tools and Inconel 718 type material. Results of the study indicate that high pressure coolant use has a significant effect on tool wear. It was reported that breaking of continuous chips was only achieved at a pressure setting of 300 bar [73] (Fig. 24).

To study the effects of high pressure jet cooling on chip breakability, cutting forces, cutting temperatures, and surface quality, Inconel 718 type material was machined using a coated carbide cutting tool. Tests used three cutting speeds, feed rate, cutting depth and pressure settings. The high pressure coolant was delivered to the tool-chip interface at an inclination angle of 6°. It was determined that increased pressure

Table 3
Effects of chip breaking using the vibration method.

	Level					
Effect	5	4	3	2	1	Description
Environmental			X			No direct environmental effect observed.
Chip breaking	X					Chip breaking achieved for all material types tested.
Machinability					X	Surface roughness and maximum cutting forces increased.
Applicability					X	Existing tools require retrofitting for vibration-assisted use.
Cost				X		Additional energy required for vibration may increase costs.

5: Positive **4**: Partially positive **3**: No effect **2**: Partially negative **1**: Negative.

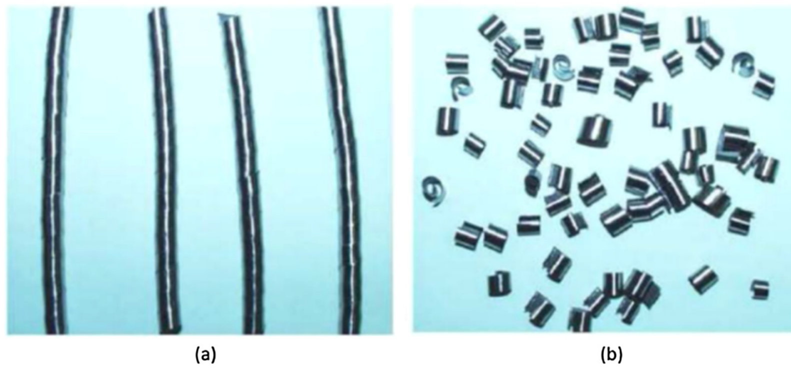

Fig. 21. a) Chips formed under a pressure of 150 bars, b) chip formations produced under a pressure of 203 bars [68].

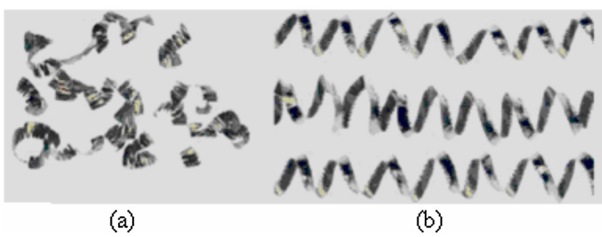

Fig. 22. a) Chips formed under 20.3 MPa coolant pressure, b) thin chip formations under conventional coolant flow [69].

reduced chip curvature radius which resulted in broken chips with smaller dimensions. It was reported that increased pressure reduced BUE (Built-Up Edge) and cutting forces [74] (Fig. 25).

Tool wear and chip breakability under pressurized cooling were studied during the machining of Inconel 718 material using SiAlON ceramic cutting tools. The study contrasted conventional cooling and pressurized cooling. The tests were conducted using a cutting speed of 300 m/min, a feed rate of 0.2 mm/rev and a cutting depth of 1.0 mm. The tests compared the results obtained from conventional cooling at 0.7 MPa and high pressure cooling at 20 MPa. It is stated that notch wear increased during machining using high pressure cooling, and that edge wear was reduced, leading to increased tool wear. It was expressed that chip curving took place earlier due to high pressure coolant use, chip-tool distance decreased and chip breaking took place [75] (Fig. 26).

A hole drilling study was conducted to study the relationship between high pressure cooling and chip breakability, using TiAl6V4V type material. All cutting tests were conducted at a fixed cutting speed of 80 m/min, with a feed rate of 0.15 mm/min. Hole depth was set at 30 mm. The study utilized coolant pressure settings of 10 bar, 30 bar, 40 bar and 70 bar, and varying nozzle diameters of 1.0–1.2–1.4–1.7–2.0–2.5 mm. Tests results indicated that targeted chip formations were achieved with increased pressure and nozzle diameter values. The desired chip formations were obtained at pressure setting of 30 bar and nozzle diameter of 1.7 mm [76] (Fig. 27).

In addition to using cooling fluid pressure for chip breaking, it is known that widely used cooling methods also have direct and indirect chip breaking effects. Several scientific studies have analyzed operational performance of various cooling methods. In one such study, four methods of cooling have been studied: dry, wet, MQL (Minimum

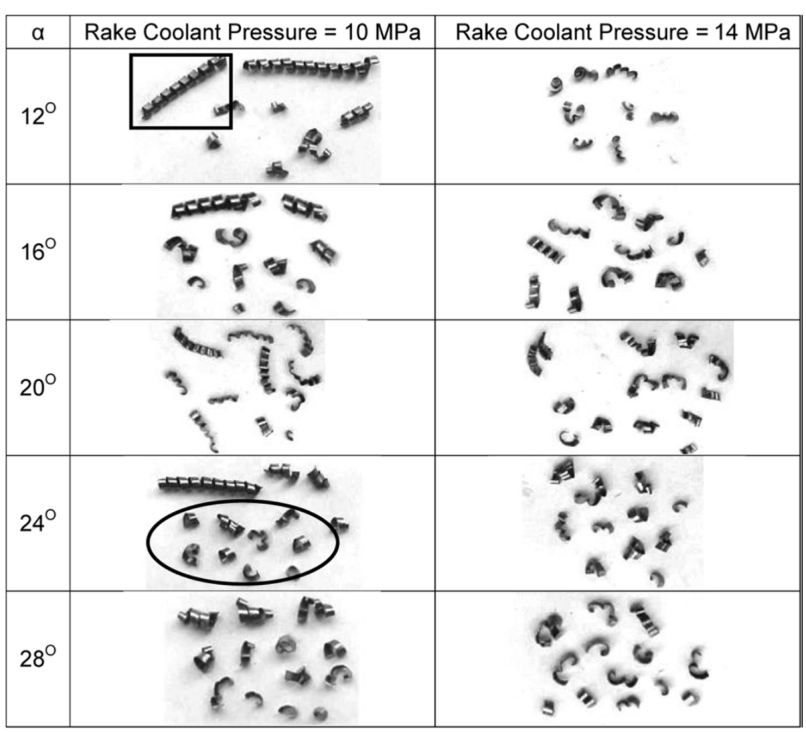

Fig. 23. Varying chip formations for nozzle inclination angle and coolant pressure [70].

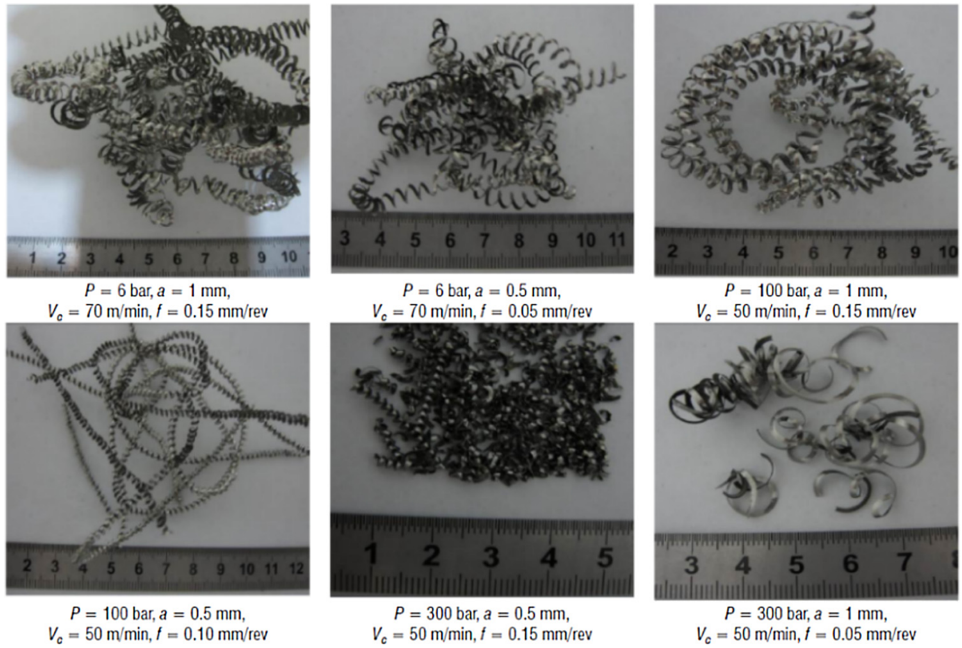

Fig. 24. Chip formations per pressure settings [73].

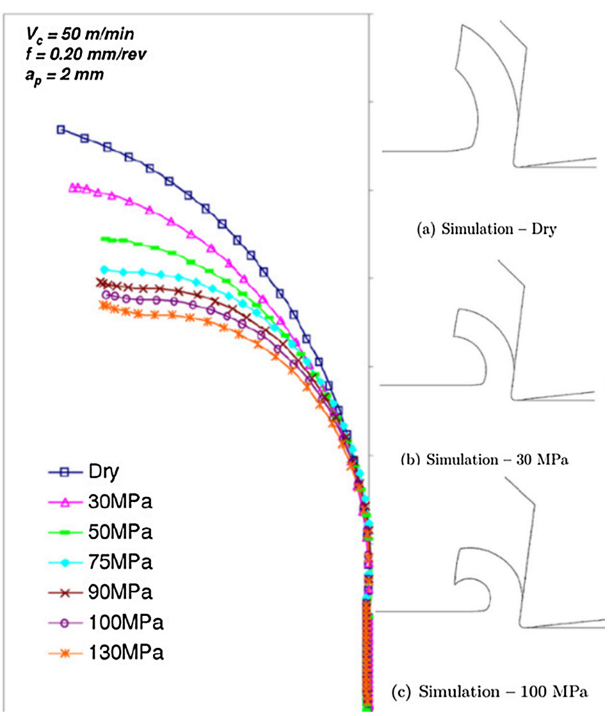

Fig. 25. Change in chip curvature radius against varying pressure values [74].

Quantity Lubrication), and MQL plus cooled air. The effects of cooling methods on cutting forces, tool wear, surface roughness, and chip morphology were examined by lathe turning of TiAl6V4V type material. Cooled air delivered to the cutting zone at −15 °C along with MQL was observed to improve cutting performance, resulting in smaller chip formations [77]. In the turning of 17-4 PH type stainless steel, dry, wet, MQL and cryogenic processing methods were compared and their effects on cutting performance were examined at multiple cutting depths. Cryogenic processing was determined to provide the best results in terms of machinability parameters and chip formation [78]. Additionally, wet and cryogenic processing in drilling operations were compared in terms of cutting temperatures, tool life, and chip breakability. It was determined through the comparative study that cryogenic processing resulted in better performance [79,80]. In cryogenic processing, it is recognized that chips produced from low carbon and ductile material increase in breakability when cooled to temperatures below the ductile-to-brittle transition temperature. For this reason, cryogenic cooling was applied and chip temperature was lowered to below −55 °C, leading to chip breaking upon collision with breakers as breakability and embrittlement increase. Consequently, it is observed that cryogenic processing improves chip breaker performance [81,82]. In a similar fashion, various tests have demonstrated that cooling strategy has significant effects on chip morphology, with cryogenic cooling laying the groundwork for chip breaking by decreasing chip ductility [83,84] (Fig. 28).

The effects of compressed cool air jets on machining efficiency and chip formation have been experimentally studied in turning operations. In the study, TiAl6V4V type material was used with three cutting speeds, feed rates and cutting depths and the use of dry conditions were compared to air cooling processes. The coolant pressure was maintained at a constant 7 bar value during the tests, and cutting temperature, tool wear, surface roughness, and chip formation were examined. The study results indicated that the cool air jet improved cutting temperature, tool wear, and surface quality. With the use of air cooling, chip dimensions were reduced and machinability performance was improved [85] (Fig. 29).

Chip breaking using high pressure coolants have been applied to various materials utilizing multiple operations. Chip breaking under pressure takes place at varying pressure settings for different materials; it was observed that pressure values higher than 20 MPa are required. This in turn requires further development of tool hardware. Additionally, it is reported that high pressure cooling increases notch wear in tooling, leading to degradation in tool life [68,75]. Furthermore, it is a recognized fact that cooling fluids have harmful effects on humans and the environment. These lead to restricted use of coolants [67]. The effects of chip breaking using coolants are shown in Table 4.

Chip breaking effect of specialty breaker apparatus

Chip breaking using chip breaker apparatus was developed in response to methods (described above) falling short of expectations and to mitigate their shortcomings. As such, the design of specialized chip

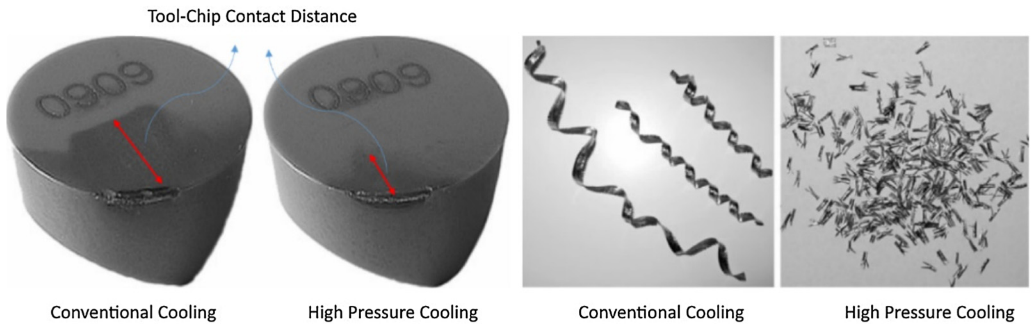

Fig. 26. Tool-chip contact distance variations and chip formations influenced by high pressure cooling [75].

breaker apparatus or tool holders is one of the solutions developed to tackle continuous chip formations. A specialized tool holder was designed to act as an obstruction for continuous chip flow with the use of which the chip will break upon collision; the goal is for the chip to break upon collision against obstacles in different regions, based on orientation of the chip flow. As indicated in Fig. 30, a high side-curl speed will result in collision with regions a and/or b, while a high up-curl speed will result in collision with region c, with the goal of causing chip breaking to take place. The results of the study indicate better chip breaking performance at low cutting speeds, with lower feed rates leading to yet further improvement in chip breaking [86]. However, the designed system fell short of expectations in chip breaking performance for chips produced by the machining of Inconel 718 material [12].

A custom tool holder was designed generating oscillating motion, allowing vibrations to be produced on the tool holder itself with the use of a cam mechanism. The cam is driven with a motor, and the tool holder in turn oscillates thanks to the cam. With the help of the aforementioned custom tool holder, the continuous chips formed under all cutting conditions and for all material types were successfully broken. However, despite the success of the system in chip breaking, surface roughness significantly deteriorated and was measured at a value of 6.3 µm Rz [87] (Fig. 31).

As a solution to the continuous chip formation problem, the use of a guide tunnel was proposed to dispose of chips by chip pulling. Guiding grooves were cut into the tool to disable chip curving and to guide chips into the aforementioned tunnel [88]. The grooves, having a radius of 0.05 mm, were machined into the rake face using EDM (Electrical Discharge Machining). The tunnel for chip flow was designed to have four parts. To allow for free flow of the chip inside the length of the tunnel, the dimensions of tunnel parts were gradually increased. Tests were conducted using cold rolled steel at four different cutting speeds, feeding rates, and chip flow angles. It was reported that no significant changes were observed in cutting forces with respect to varying chip flow angle. In chip control through chip pulling, forces and chip thickness were observed to be reduced [89]. In the method so developed, the grooves cut into the tool resulted in additional costs being incurred, as standardized cutting inserts need to be developed that are compatible with the newly designed system. Other problems facing the method are the applicability of the system for pulling chips and its adaptation to varying material types (Fig. 32).

A custom tool holder capable of delivering liquid nitrogen (LN_2) to the cutting zone was developed, to allow for chip breaking and to prolong tool life in the machining of titanium alloys. Contingent on accurate and precise positioning of the chip breaker, successful chip breaking was reported. The study also reported extended tool life [90] (Fig. 33).

A dynamic chip breaker was designed to break continuous chips formed during the machining of Inconel 718 type material. An apparatus, affixed onto the tool holder using screws, was utilized for chip breaking. The dynamic chip breaker was driven using a DC motor. Using the aforementioned apparatus, successful chip breaking was observed under all conditions in tests conducted using four cutting speeds, feed rates, and cutting depths. It was stated that the chip breaker produced acceptable surface finishes [91].

The dynamic chip breaker design was then developed and the effects of the chip breaker apparatus on chip breaking capabilities and cutting parameters were analyzed. A gearbox was used in the new design and motor drive was applied through the tool holder (Fig. 34). The study revealed that chip formations were successfully broken. Thanks to the chip breaker apparatus, improvements were observed with respect to heat generation and cutting forces, the negative effects of chip formation on surface roughness were eliminated, and improvements were

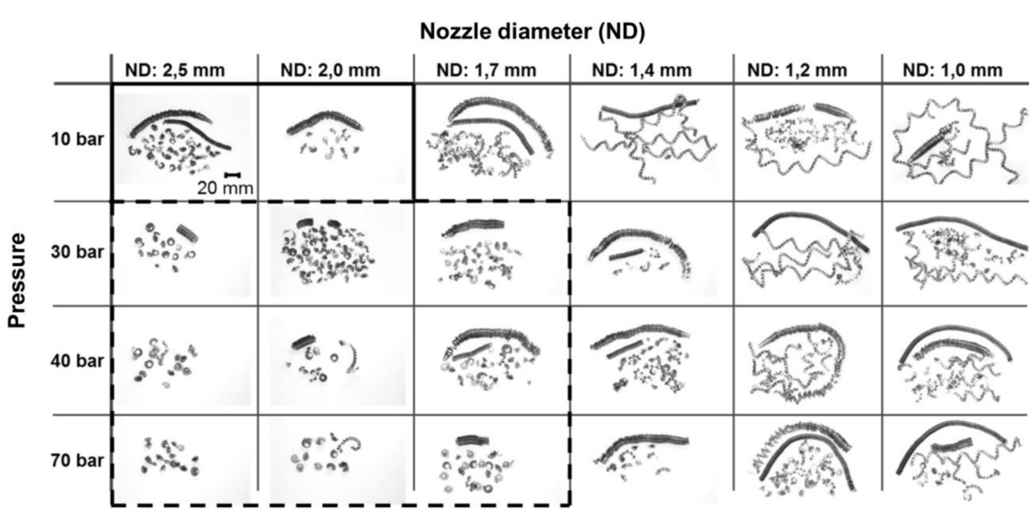

Fig. 27. Chip formations varying with pressure and nozzle diameter values [76].

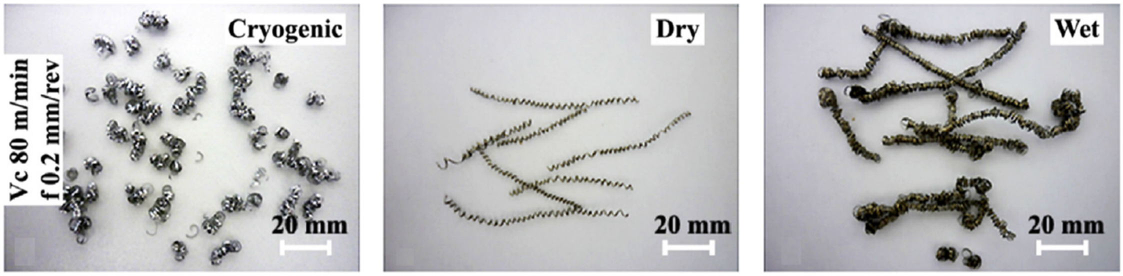

Fig. 28. Effects of various cooling methods on chip breaking [83].

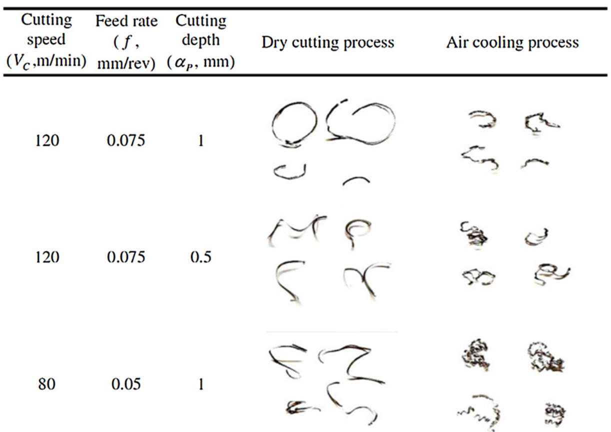

Fig. 29. Effects of air-cooling process on chip breaking [85].

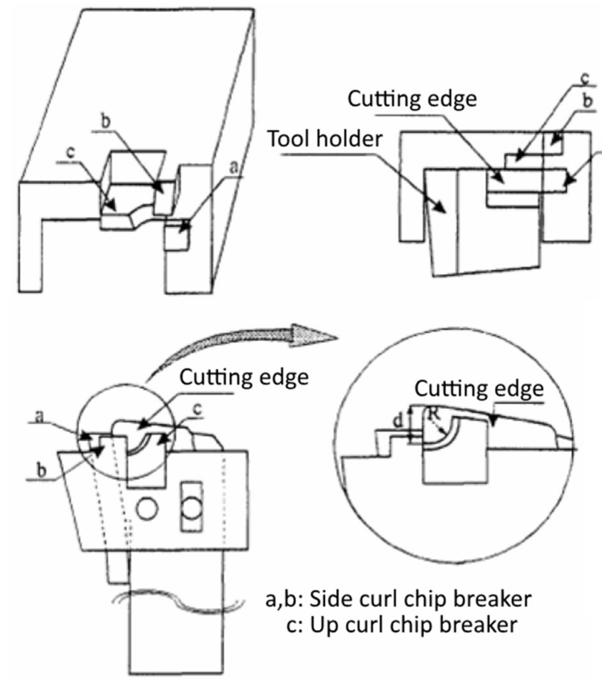

Fig. 30. Tool holder design for chip breakers [86].

also observed for lower cutting depth and higher feed rate values [4,92] (Fig. 35).

In many cases, the use of breaker apparatus for chip breaking has led to efficient and effective results. However, attention must be paid to make certain that the designed apparatus does not lead to increased costs, does not negatively impact overall tool operations, and/or impede routine activities such as the changing of cutting inserts during operations, and most importantly, that it possesses a high level of applicability. The effects of chip breaking using breaker apparatus are shown in Table 5.

Results and evaluation

The present literature survey revealed five methods used for continuous chip breaking and for alleviating its adverse effects listed below:

1 Modification of cutting parameters: Increased feed rate and cutting depth have been reported to increase chip breakability. However, increases in these two parameters in turn adversely affected cutting forces, temperatures, and consequently, tool life and surface quality. Additionally, tool capacity and features place limits on modifications made to the parameters.
2 Use of chip breaking geometries on the cutting insert: The chip breaking grooves machined onto the cutting insert have been reported to be effective in chip breaking by reducing chip curvature radius. Additionally, they were found to positively affect cutting forces, temperatures, and surface quality. However, the machining of the grooves leads to increased tooling costs, and chip breaking geometries were found to be inadequate when used for ductile materials such as Inconel 718.
3 Chip breaking using vibration: Chip breaking through the use of vibration, achieved by severing the contact between the cutting tool and the workpiece at certain frequencies, is a successful method. It has been shown to be effective across all material types and

Table 4
Effects of chip breaking using coolants.

Effect	Level 5	4	3	2	1	Description
Environmental					X	Coolant use negatively affects the environment.
Chip breaking	X					Effective chip breaking achieved for all material types tested (minimum 20 Mpa).
Machinability		X				Parameters for machinability were improved for specific conditions. However, high pressure led to increased tool notch wear.
Applicability					X	Existing tools require retrofit with high pressure hardware.
Cost				X		Delivery of high pressure may increase energy costs.

5: Positive **4**: Partially positive **3**: No effect **2**: Partially negative **1**: Negative.

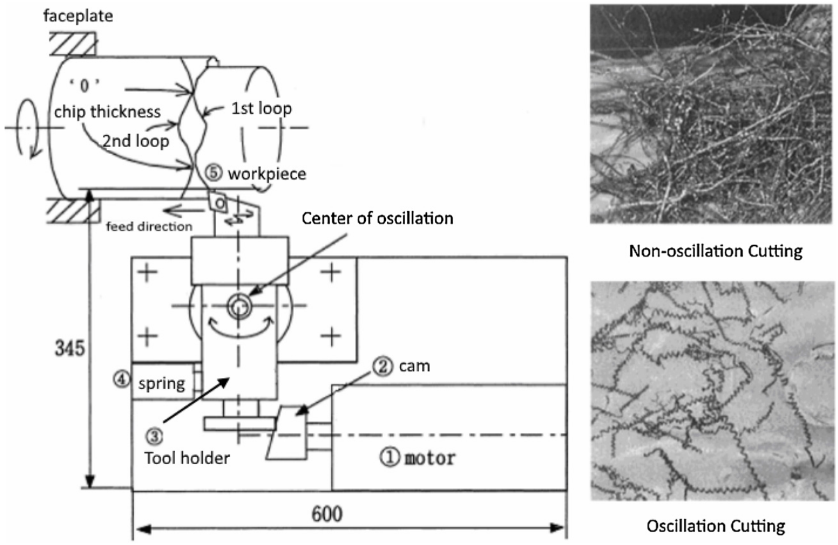

Fig. 31. Oscillating chip breaker apparatus design and its chip breaking effect [87].

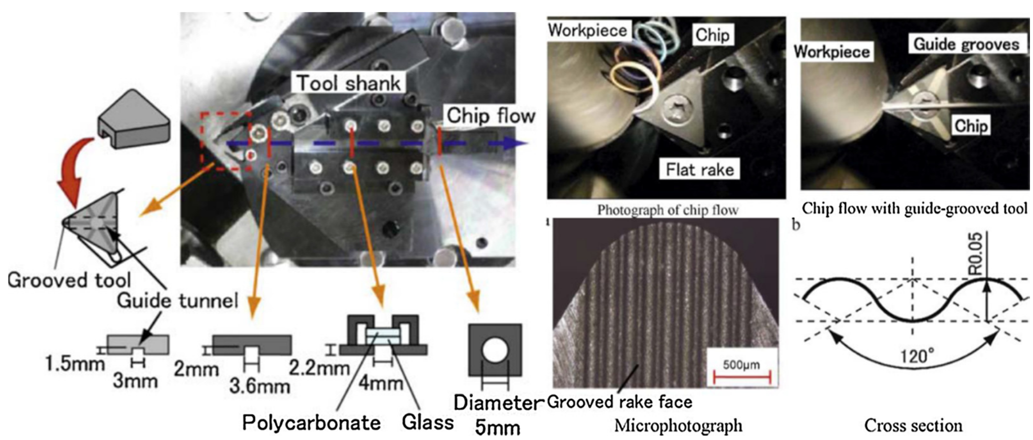

Fig. 32. Guide tunnel and cutting tool design enabling chip flow [89].

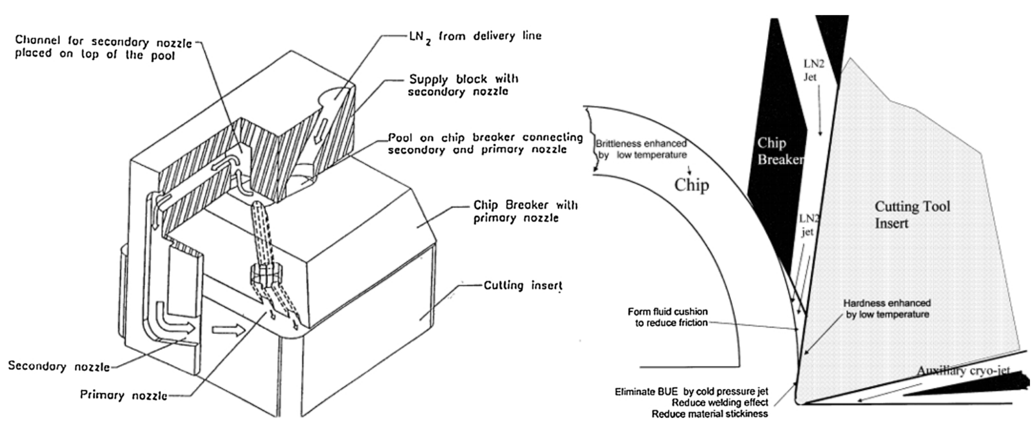

Fig. 33. Schematic illustration of cryogenic processing method [90].

operational parameters. However, the targeted surface quality is not achieved. Additionally, tool hardware is prone to adverse effects of the generated vibration. For direct generation of vibration, the conforming CAM modules need to be derived.

4 Use of pressurized coolants: The use of coolants that improve operational efficiency have led to effective chip breaking through the use of high pressures employed therein. Chip from such ductile materials as Inconel 718 were reported to be broken at pressure of 20 MPa. High pressure values increasing notch wear on the cutting tool and incompatibility between the tool and the high pressure coolant systems are cited as some of the problems associated with this method.

5 Use of custom breaker apparatus: The performances of custom chip breakers vary in terms of their effectiveness. These devices, designed to target varying material types and operational conditions, have positive outcomes as well as various inadequacies, but overall, have

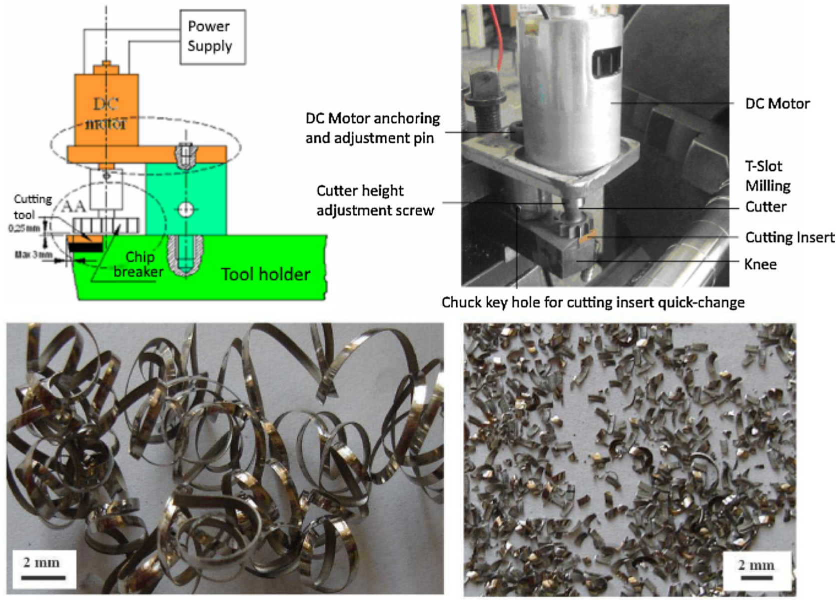

Fig. 34. Design of dynamic chip breaker apparatus and its chip breaking effect [91].

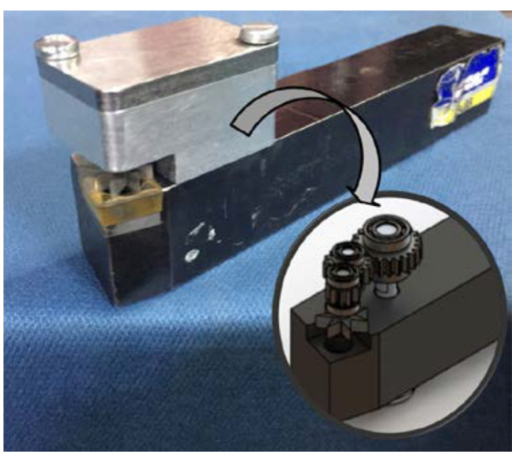

Fig. 35. Custom developed chip breaker [92].

been observed to be effective in chip breaking. These systems provide high performance in return for lower costs, but need further development in terms of applicability and tool compatibility.

Based on the evaluation of the data in Tables 1 through 5, inclusive, it is observed that the chip breaking effects of chip breakers surpass other methods with respect to machinability and applicability, while, in certain cases, lack effectiveness on ductile materials. At the same time, chip breakers are observed to have no negative effects on the environment when compared with other methods. These considerations make chip breaking using chip breaker geometries superior to other methods.

In those cases where chip breaker geometries prove inadequate, the use of breaker apparatus or coolant fluids may be proposed as remedies. The negative effects of coolant fluids on the environment make the use of breaker apparatus more advantageous. Readily available commercialized breaker apparatus with high applicability will contribute to solving the chip breaking problem. Similarly, development of environmentally-friendly coolants and their use in tools for high pressure chip breaking applications should contribute significantly to providing solutions to the problem of chip breaking.

Table 6 shows the materials used in the evaluation of the various methods tackling continuous chip formation, and the corresponding methods used. Researchers were studied to break the continuous chips using different methods such as varying cutting variables, using various on-tool chip breaker geometries, utilizing oscillating technics, employing pressurized coolants and designing custom chip breaker. The long chips are common difficulty in finishing and semi-finishing process of ductile metals such as aluminum, ductile steels, and superalloys and breaking the continuous chips improves the automation and production management. While having positive aspects, solutions developed for preventing the formation of continuous chips do come with certain drawbacks, which have significance due to the outcomes involved. Therefore, the disadvantages of employed chip breaking methods were compared based on the workpiece surface quality, cutting forces, tool life, cutting temperatures, machining costs and ease of use. The employed chip breaking methods and disadvantages depending on the type of the machining materials are given in Tables 6 and 7, respectively.

Table 5
Effects of chip breaking using breaker apparatus.

	Level					
Effect	5	4	3	2	1	Description
Environmental			X			No direct environmental effect observed.
Chip breaking	X					Effective chip breaking achieved for all material types tested.
Machinability		X				Apparatus observed to produce acceptable effects.
Applicability					X	Commercialization and availability of apparatus need to be developed.
Cost				X		Design and use of apparatus may lead to additional costs.

5: Positive **4**: Partially positive **3**: No effect **2**: Partially negative **1**: Negative.

Table 6
Chip breaking methods applicable to various material types.

Method employed						
Material machined		Varying of Cutting Parameters	Use of Various On-tool Chip Breaker Geometries	Use of Vibration	Use of Pressurized Coolants	Use of Custom Chip Breakers
Carbon Steel	1040	•	• • •			
	1045	•	• • •			
	1050	•	• • •			
	1080	•	• • •			
Tempered Steel	4140	• •	• • •	•		
	4340	• •	• • •	•		
Stainless Steel	304	• •	• • •	• •		• •
	316	• •	• • •	•		• •
	316 L	• •	• • •	•		• •
Cast Iron	GGG50		• • •			
Super Alloys and Specialty Materials	Ti6Al4V			•	• •	• • •
	Inconel 718			•	• •	• • •
	Al2024				• •	• • •
	Al6061			• •		• • •
	AlCu4Mgl		• • •		• •	

• • • : Widely used.
• • : Frequently used.
• : Less frequently used.

Table 7
Drawbacks of chip breaking methods.

Method employed					
Drawbacks	Varying of Cutting Parameters	Use of Various On-tool Chip Breaker Geometries	Use of Vibration	Use of Pressurized Coolants	Use of Custom Chip Breakers
Degradation in Surface Quality	•		•		
Increases in Cutting Forces	•		•		
Reduction in Tool Life	•			•	
Increase in Temperatures	•				
Feature Not Supported by Tool			•	•	
Increases in Cost		•		•	•
Complexity of Use			•	•	•

Compliance with ethical standards

- There are no potential conflicts of interest
- Human Participants and/or Animals were not used in the research
- Informed consent was shown in acknowledgement section.
- The manuscript has not been submitted to more than one journal for simultaneous consideration.
- The manuscript has not been published previously and the paper has not been split into several parts to increase the quantity of submissions.
- All experimental data was measured and confirmed and the test results were not manipulated (including images) to support my conclusions.

Declaration of Competing Interest

There are no potential conflicts of interest, financial interests/personal relationships which may be considered as potential competing interests.

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