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DISCONTINUOUS CUTTING: FAILURE MECHANISMS, TOOL MATERIALS AND TEMPERATURE STUDY – A REVIEW

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Abstract. Complexity is one of the trademarks of modern machining processes. In this sence, discontinuous cutting is attracting the interest of researchers. This paper presents a review on discontinuous cutting identifying the main topics related with this special kind of operation. The constant knocking between the tool and the workpiece, and thermal cycles that have to face the workpiece make needed to analyse specifically discontinuous cutting, being tool failure and the selection of tool materials critical issues to deal with. Besides, the thermal effects in discontinuous cutting have been studying with two different approaches: direct temperature measurement and temperature prediction by using mainly analytical and numerical models. Another strategy is the use of cutting fluids that have been a conventional strategy to diminish the negative influence of the thermal effects. However, the need to guarantee environmentally friendly manufacturing processes is encouraging the use of new cooling/lubricating strategies such as, among others, dry machining, MQL system or cryogenic refrigeration.

1. INTRODUCTION

Conventional machining processes, such as turning, drilling or milling, are the most widespread metal shaping processes in the manufacturing industry [1,2]. Traditionally, they have been analysed by means of continuous cutting. In particular, continuous turning has been analised according to the standard ISO 3685:1993. However, this kind of studies is not fully representative of modern machining operations where increasing complexity is one of the biggest challenges to face. Complexity is manifested in both products and manufacturing processes. In the last case, nowadays it is usual to have to deal with discontinuous cutting processes in which coexist cycles of cutting and non-cutting operations [3,4].

Discontinuous cutting processes can be a result of the geometry of the workpieces that can include holes, lubrication channels, splines or key slots [5-6] or due to production needs. In the last case, the cutting process involves the repeated termination of cutting cycles for short intervals due to production requirements [4].

Although in the specialized literature there is not an adopted clear distinction between the two cases introduced above, according to Johansson and Sandqvist [7] it is possible to make such distinction. So, discontinuous cutting processes can be divided into: intermittent cutting, where workpiece includes discontinuous surfaces, for instance the case of turning as the one of the research of Rubio *et al.* [8]; and interrupted cutting, where the production needs are the cause of the interruptions, existing periods in which the tool is not cutting, for instance the case of milling as the one analysed by Armendia *et al.* [9]. This classification can be seen

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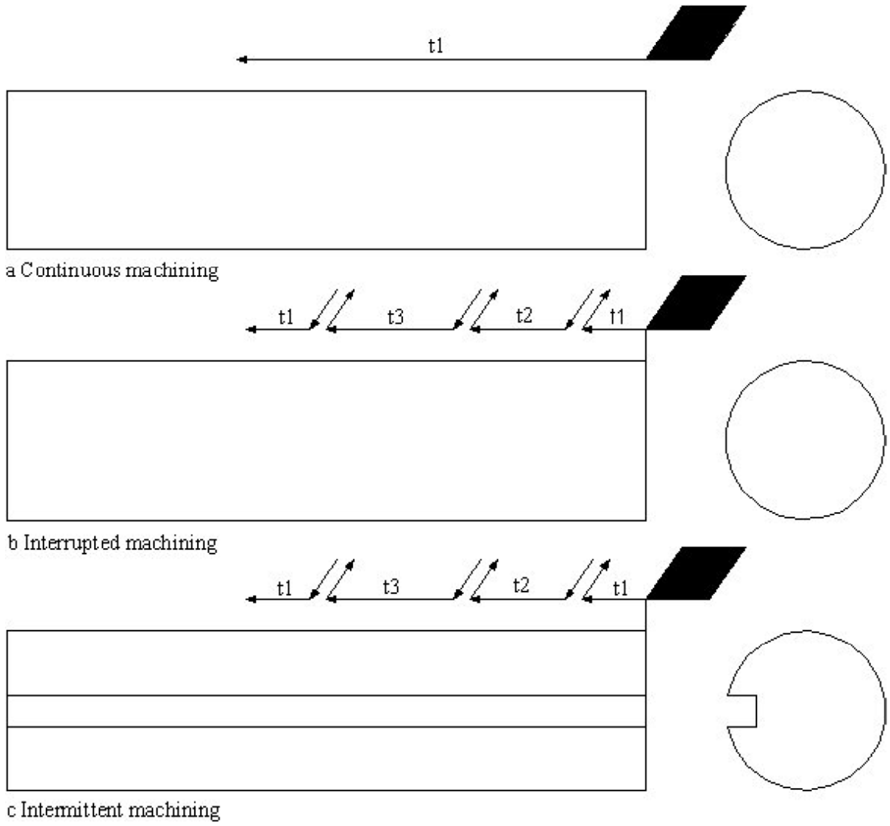


Fig. 1. Types of cutting processes. Based on Johansson and Sandqvist [7].

in Fig. 1, in which the continuous case and the two cases of discontinuous cutting are identified in turning.

The existing differences among continuous and discontinuous cutting make not possible to transfer the results obtained under the continuous cutting investigations to the discontinuous ones [10].

The machining processes, both continuous and discontinuous, have in common problems associated with tool wear or tool failure due to, mainly, the friction and the temperature reached in the workspace area. These problems are reflected, in general, in a surface finish that does not achieve the adequate level. Different researchers have made important efforts in order to solve them. In the continuous case, they investigated the use of the lubrication and cooling techniques and their relationship with tool wear and surface roughness. And, in the discontinuous case, they studied the temperature effects, tool failure and tool materials. The following sections cover the main works related with these investigation topics.

2. TOOL FAILURE MECHANISMS

The especial characteristics of the discontinuous cutting processes: the constant knocking of the tool against the workpiece, in the intermittent one, and the temperature changes due to the combination of periods with and without cutting operations, in the interrupted one, make likely the catastrophic failure of the tool. The tool failure mechanisms in the discontinuous cutting include: thermal cracking, mechanical impacts, adhesion mechanisms, negative shear angle, incipient chip deformation and a combination of different mechanisms that are summarized in Fig. 2. Following, a detailed explanation of these failure mechanisms is given along with the main researchers that have investigated in this field.

Thermal cracks

The thermal effects on the tool were studied by several researchers, and their influence on tool cracking is widely accepted. So, Boston and Gilbert [11] were reported to be the first ones in identifying thermal effects to be the cause of cracks in the rake face of carbide tools during milling [12]. Microcraks due to thermal effects were also identified by Okushima and Hoshi [13,14]. Likewise, Bhatia *et al.* [15] and Chandrasekaran and Venkatesh [16] state that the thermal cracking is the main root of failure at high cutting speeds due to the high temperatures achieved and the high degree of tempera-

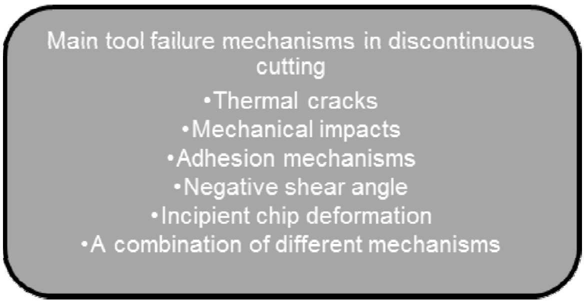


Fig. 2. Failure mechanisms on discontinuous cutting.

ture variation. Tönshoff *et al.* [17] also identified thermal cycles and mechanical stresses as a source of microcracks, chipping and sometimes catastrophic failure of the cutting edge in milling processes.

The works by Zorev [18] and Zorev and Sawiaskin [19] state that the tensile strength induced in the body of the tool during non-cutting periods is responsible for the crack formation. Braiden and Dugdale [20] identify the roots of the cracks in the refrigeration owing to the inelastic behaviour of the tool during heating. Yellowley and Barrow [21] identify the importance of the thermal strain and the number of heat cycles in tool life.

Work by Xu *et al.* [22], on ceramic tools, justified the formation of thermal cracks due to the variation of temperatures on the tool faces. This variation leads to the existence of a cyclic action of tensile and compressive stresses that will end fracturing the tool. The larger the temperature difference, the easier the cracks will be formed.

Mechanical impacts

Kronenberg [23] studied the influence of the entrance conditions of the tool in face milling during intermittent cutting, finding a clear influence of entrance conditions in tool life. So, when the tool entrance angle is higher than 25°, tool life diminishes. Studies by J.H.L. The [24] also identify the influence of the entrance conditions in the formation of cracks. Rotberg *et al.* [25] analyse the influence of the entrance and exit conditions by means of a vibration signal, identifying the entrance as a most unfavourable case. From another side, the investigation by Diniz and Filho [26] gives more importance to the entrance conditions than to the exit conditions.

From other side, Hoshi and Okushima [27] state that the exit conditions are more important than the entrance conditions. Besides, the influence of the exit conditions is identified by different studies [28-30].

Works by Andreev [31,32], Kuljanic [33], and Zorev [18] do not identify the influence of the entrance and exit conditions as important issues in tool life. However, lately Zorev and Sawiaskin [19] recognise the influence of the mechanical impacts in the propagation of the cracks generated by the thermal effects. Studies led by Tornachi and Dugdale [34] and by Bhatia *et al.* [35] allowed confirming that the mechanical impacts can cause the failure of the carbide tools.

Finally, Shintani *et al.* [36] recognize that the impact mechanism between the tool and the workpiece has a great influence on the tool failure mode during interrupted cutting. In particular, it is observed that the tool geometry can help to diminish the occurrence of failures if it is conveniently adapted to the mechanical impacts to withstand.

Adhesion mechanisms

Andreev [37] and Kabaldin [38] identify the appearance of adhesion processes on the tool during intermittent cutting with carbide tools. Moreover, Yellowley and Barrow [39] identify the adhesion mechanisms as a source of tool failure.

Negative shear angle

Pekelharing [28] states that the tool chipping occurs due to the formation of a negative shear angle, because the rotation of the primary shear plane, in the exit movement of the tool, increasing the force on the edge of the cutting tool and generating a dangerous stress distribution in the tool. This phenomenon is named “foot forming”.

The experimentations in interrupted turning and milling show how the workpiece material has a great importance on the effects of the exit conditions in the results obtained. So, in the machining of grey cast irons, the exit conditions do not have influence on tool life, while during the machining of stainless steels a premature failure can occur regardless of whether a “foot” is formed [40].

In relation with the stress generation, during the exit of the tool in intermittent cutting, Dokainish *et al.* [41] show how the relation between the width of the chamfer and the depth of cut has an important role in the stress generation that can lead to tool failure. In particular, it is observed how for depth of cut equal to the chamfer width the likelihood of tool failure is reduced. Likewise, Astakhov [42] identifies the stresses as a major cause for poor tool life under intermittent cutting; being shear stresses 30% higher than in continuous cutting. The stress concentration at the cutting edge is also identified by

Ezugwu and Tang [43] as a source for the deformation of the cutting edge, developing chipping processes.

Incipient chip deformation

The importance of the incipient chip deformation following the first contact between the tool and the workpiece is stated by The J.H.L. [24] as a cause for tool failure.

A combination of different mechanisms

A combination of some of the mechanisms introduced above can occur during discontinuous cutting processes according to Zorev and Sawiaskin [19]. In their findings, they state that a combination of mechanical impacts and thermal effects can lead to tool failure. Likewise, Xu *et al.* [22] and Cui *et al.* [44] observed that in combination the mechanical impacts and thermal effects can affect the performance of the ceramic tools during intermittent turning of steel.

3. TOOL MATERIALS

Tool material selection represents an important decision in cutting processes in terms of productivity [45]. During cutting, the tools are exposed to wear, mainly, due to abrasion, adhesion and diffusion [46].

A strong development of tools, especially within the 20th century, has been produced. This development allows manufacturers to face more difficult cutting processes. To a large extent, the base materials used on tools are responsible for this advance, highlighting the importance of the apparition of materials such as high speed steel (HSS), cubic boron nitride (CBN), cemented carbide, cermet, ceramic or polycrystalline diamond (PCD) [47-49].

Besides the evolution of tool base materials, another trend in the development of tools is the investigation on coating technology. The use of coatings allows to work at worse operative conditions, by means of improving the friction and wear resistance properties of the tools [50]. The main coating systems include: self-lubricating, CBN, chemical vapour deposition (CVD)-diamond and supernitrides [49]. Work by D'Errico *et al.* [51] analysed the use of physical vapour deposition (PVD) coatings on cermet tools during interrupted cutting, recognizing that the beneficial effects of coatings are limited because the films can be removed due to the constant impacts during interrupted cutting.

The difficult conditions that the tools have to face during discontinuous cutting make tool material selection an important factor for the success of the cutting process. So, the study of the behaviour of different tool materials turns into one of the main lines of investigation in discontinuous cutting for researchers.

The following points include a review of several investigations on the tool materials used in discontinuous cutting, summarizing the main experimental works in Table 1 and Table 2, focusing on tool materials tested and investigation topics, respectively.

3.1. Cemented carbides

Cemented carbides are produced by using a metallic hard material that is sintered at high pressures and temperatures with cobalt as binder [49].

The tool wear of cemented carbides during interrupted cutting has been analysed by several re-

Table 1. Tool materials tested in experimental works in discontinuous cutting.

Tool material	Workpiece material (process)
Cemented carbide	Nodular graphite cast iron (turning) [54]
Uncoated carbide (WC): H1	Ti6Al4V titanium alloy (turning) [55]
Cemented carbide	Assab steel 760 (HV 221) (turning) [56]
CBN: Sandvik CBN 7020 and CBN 7050	SAE 01 Hardened steel (turning) [5]
CBN: Sandvik CBN 7020 and CBN 7050	AISI 4340 steel (turning) [57]
CBN	JIM-SCM 420 carburized steel (turning) [36]
CBN: BN250 (60% CBN TiN), BNX4 (70% CBN TiN), and BN100 (80% CBN TiN)	AISIE-52100 steel (turning) [58]
CBN: CBN-L and CBN-H	M50 steel (turning) [59]
PCBN: BN250 and BZN6000	M50 steel (turning) [60]
PCBN: Amborite DBC50 and Amborite DBN45	1137 Hardened steel (turning) [61]
Ceramic Al_2O_3-(W, Ti)C	AISI 1045 hardened steel (turning) [44]

CBN: Sandvik 7015 and 7025Ceramics: Sandvik CC670 and CC650	AISI 4340 hardened steel (turning) [62]
Ceramic: silicon nitride-based ceramic Carbide coated (TiN and Al_2O_3) carbide	GG25 grey cast iron (face milling) [63]
Ceramic: TA (Al_2O_3/15vol.%SiC/15vol.%Ti(C,N)), TB(Al_2O_3/15vol.%SiC/15vol.%(W,Ti)C), TC(Al_2O_3/45vol.%Ti(C,N)/RE), TD(Al_2O_3/45vol.%(W,Ti)C/RE), TE(Al_2O_3/45vol.%(W, Ti)C) and TF(Al_2O_3/30vol.%TiC/Carbon)	#45 mild carbon steel (turning) [22]
Ceramic: alumina-based ceramic reinforced with SiC whiskers PCBN	AISI 4340 steel (turning) [6]
PCD Carbide K10	GK-AlSi17Cu4FeMg die cast alloy (turning) [65]
PCD Uncoated K68 insert Microcrystalline diamond film coated Nanostructured diamond coated	A390 aluminium-silicon alloy (turning) [66]

Table 2. Main topics investigated in experimental studies in discontinuous cutting.

Investigation topics	Authors
Tool life / tool wear	Diniz *et al.* [5], Oliveira *et al.* [6], Xu *et al.* [22], Shintani *et al.* [36], Cui *et al.* [44], Sayit *et al.* [54], Diniz and Oliveira [57], Chou [59], Chou and Evans [60], Godoy and Diniz [62], Diniz and Ferrer [63], König and Erinski [65] and Liang *et al.* [66].
Surface roughness	Oliveira *et al.* [6], Shintani *et al.* [36], Sayit *et al.* [54], Pavel *et al.* [61], Ko and Kim [58], Chou and Evans [60], Godoy and Diniz [62], Diniz and Ferrer [63], König and Erinski [65] and Liang *et al.* [66].
Cutting forces	Wang *et al.* [55], Choudhury *et al.* [56], Ko and Kim [58], Chou [59] and Chou and Evans [60].
Tool geometry	Shintani *et al.* [36], Choudhury *et al.* [56] and Diniz and Oliveira [57].
Wear mechanisms	Diniz *et al.* [5], Oliveira *et al.* [6], Xu *et al.* [22], Shintani *et al.* [36], Cui *et al.* [44], Diniz and Oliveira [57], Ko and Kim [58], Pavel *et al.* [61], Godoy and Diniz [62], Diniz and Ferrer [63], König and Erinski [65] and Liang *et al.* [66].
Cooling systems	Wang *et al.* [55].
Chip morphology	Wang *et al.* [55].
Friction	Wang *et al.* [55].
Stresses	Shintani *et al.* [36] and Wang *et al.* [55].
Accelerations	Ko and Kim [58].
Angles	Cui *et al.* [44] and Wang *et al.* [55].

searchers. Thus, Campbell [52] compares the use of cemented carbides and HSS tools. In the case of titanium machining, cobalt-containing HSS tools, such as M33, M40, and M42, and the straight tungsten carbide grade C-2 (ISO K20) are used. The use of carbides allows to obtain an improvement of around 60% in metal removal rate, but HSS tools have better results in terms of chipping during interrupted cutting. Besides, in the case of superalloys, HSS tools (M33 and M42) are recommended in comparison with carbides tools due to their greater resistance to chipping and breakage, and their greater heat resistance. In this line, Ezugwu *et al.* [53] show how cemented carbide tools can be suited for interrupted cutting of nickel-based alloys at low cutting speeds. In particular, the K20 grade (cemented carbide) gave an optimum performance when milling nickel-based alloys (Nimonic 75 and Inconel 718) at various cutting conditions. The main failure mechanisms in carbides are chipping and/or fracture of the tool edges.

The influence of the cutting speed and feed rate on tool wear has been assessed in the experimentations by Sayit *et al.* [54] when machining a nodular grey cast iron. Less tool wear appeared in the cemented carbides in continuous cutting, while some differences appeared in the interrupted case due to the cutting speed and feed rate. So, increasing the cutting speed leads to a decrease in the cutting time for all the workpiece materials. Moreover, the increasing of the feed rate leads to a higher tool wear, when testing interrupted cutting of a one-slot workpiece.

The type of interruptions is a point of interest when analysing discontinuous cutting. Investigations made by Wang *et al.* [55] on interrupted turning of a titanium alloy analysed different configurations of the interruptions: one-slot, two-slot and four-slot. The tests show how with the increase of the interruption, from two to four slots, the uncoated carbide inserts suffer a higher wear resulting in the increase of the cutting forces. A similar configuration is analysed by Sayit *et al.* [54]. The results depend to a great extent on the feed rate chosen. So, in general, the tool wear is higher when working at lower feed rates (0.11 mm/rev) for the four-slot workpiece, while at higher feed rates (0.32 mm/rev) the tool wear is higher in the case of the two-slot workpiece.

Choudhury *et al.* [56] studied the influence of the tool geometry of cemented carbides during intermittent cutting. In particular, they studied the effect of chamfers, addressing that the increasing in chamfer width leads to worse results in the main cutting force and feed force.

3.2. Cubic boron nitride

Cubic boron nitride (CBN) tools are compounds made by CBN as base material that is combined with a ceramic, sometimes even with a metallic binder [49]. The CBN content has an important influence on the results obtained during machining. Thus, the main wear mechanisms of CBN tools during interrupted and semi-interrupted cutting of hardened steels were investigated by Diniz *et al.* [5]. In their findings, authors show how the flank wear and crater formation are the main wear mechanism in high CBN content tool (7050) and in the case of low CBN content tool (7020) chipping/breakage. Related with tool life, better tool life results are obtained with low CBN content tools in continuous cutting. However, the high CBN content tool offers moderate better results in interrupted cutting.

Another investigation by Diniz and Oliveira [57] show how low CBN content tools outperform high CBN content tools during continuous, semi-interrupted and interrupted cutting in comparison to the high CBN content tool for the different geometries tested.

Ko and Kim [58] studied the behaviour of CBN tools during intermittent turning of AISIE 52100 steel. Their main results include the recognition that the CBN content has an important effect on tool wear and surface roughness, showing the low CBN content tools the best results.

Chou [59] presented a research on continuous and intermittent turning of hardened steel using CBN tools, addressing a better performance of the low CBN content tools during intermittent turning.

Polycrystalline cubic boron nitride (PCBN) is an improvement of CBN tools. PCBN tools were studied by Chou and Evans [60] during the machining of M-50 steel, identifying a great influence of the material in tool life. So, it can be observed how using tools with high CBN content, tool life decreases as cutting speed increases, while in the case of low CBN content, tool life reaches its maximum at medium cutting speeds. Regarding the type of interruption, the investigation shows how with the high CBN content tool there is no clear effect, but with the low CBN content tool, tool life diminishes as the frequency of interruption increases.

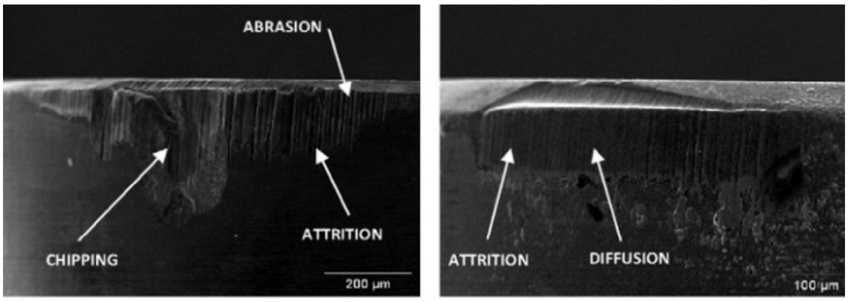
Pavel *et al.* [61] analysed the surface roughness evolution finding a different behaviour due to the type of cutting with PCBN tools of 45% and 50% CBN content. So, in intermittent cutting, the surface roughness diminishes as cutting time increases and, in continuous cutting, surface roughness increases as cutting time increases.

The tool geometry of CBN tools used in interrupted cutting is analysed by Shintani *et al.* [36]. In their work, the authors identified the influence of the collisions between the tool and workpiece on the failure of the tool. Authors studied the tool geometry, designing a new flank face that let improve tool life up to 26 times.

3.3. Ceramics

There are two basic ceramic materials that are used as cutting tools. These are aluminium oxide (Al_2O_3) and silicon nitride (Si_3N_4) [48].

The study of the application of ceramics during discontinuous cutting is done by Cui *et al.* [44]. In their work, the authors investigate the use of Al_2O_3-(W, Ti)C ceramic tools in the intermittent turning of a hardened steel. The analysis of tool wear and damage let identify that the main mechanism of tool failure is the fracture due to the combined effects of



a. CC670 – v_c = 150 m/min b. CBN-H – v_c = 150 m/min

Fig. 3. Wear mechanisms on a) ceramic tool b) CBN tool [62]. Reprinted from Journal of Materials Processing Technology, Vol. 211, V.A.A.de Godoy and A.E. Diniz, Turning of interrupted and continuous hardened steel surfaces using ceramic and CBN cutting tools, 1014-1025, Copyright (2011), with permission from Elsevier.

the mechanical and thermal stress. Moreover, the evolution of the flank wear for the different set of experiments shows that increasing cutting speed leads to an increase of the flank wear.

Comparisons between CBN and ceramics tools were done by Godoy and Diniz [62] in continuous and intermittent cutting of UNS G43400 steel, giving ceramic tools worse results in tool wear and surface roughness in all the conditions tested. Fig. 3 shows main wear mechanisms of tools. In the images, is possible to see how in the case of ceramic tools abrasion and chipping signs appeared on the surface, while in the CBN tools appeared diffusion signs. In both cases> should be replaced by <steel. The ceramic tools gave the worst results in terms of tool wear and surface roughness in all the conditions tested. Fig. 3 shows the main wear mechanisms of the tools. In the figure, it is possible to see the generation of abrasion and chipping signs (ceramic tools) and diffusion signs (CBN tools) on the surface In both cases, authors indicate the aparition of attrition signs.

Experimentations presented by Diniz and Ferrer [63] in face milling of grey cast iron analyse silicon nitride-based ceramic tools in comparison with carbide inserts with 6% of cobalt in their composition, and coating layers of TiN and Al_2O_3 with a total thickness of 5 μm. The results show how ceramic tools outperform carbides in terms of tool life.

Ceramic tools were also tested by Xu *et al.* [22] under different cutting conditions: group A: cutting speed (v) = 118 m/min, depth of cut (ap) = 0.5 mm; group B: v = 188 m/min, ap = 0.3 mm; and group C: v = 264 m/min, ap = 0.1 mm. All the tests used a feed rate of 0.1 mm/rev. Tool materials used in cutting experiments are identified in Table 1. The investigation shows that the ceramic tools offer good results in terms of tool wear and fracture resistance, during both continuous and intermittent cutting. Analysing intermittent cutting, the fracture resistance depends highly on the tools tried. The best results are obtained with TC (Al_2O_3/45vol.%Ti(C,N)/RE) and TD(Al_2O_3/45vol.%(W,Ti)C/RE) tools.

Cutting conditions have a great influence on the forms of fracture. Under group A cutting conditions, the main fracture forms include fracture on the rake face and fracture on the flank face. Ceramic tools bear mainly mechanical impact since the cutting speed is low and the depth of cut is large. Under groups B and C cutting conditions, the thermal fracture on the rake face and fracture on the flank face are the dominant fracture forms. The tools mainly undertake thermal shock and the combination of mechanical impact and thermal shock.

Under group C cutting conditions, some radial net-shaped or comb-like cracks or cracks perpendicular to the flowing direction of chips can be observed mainly as a result of the action of thermal shocks and thermal stresses.

Oliveira *et al.* [6] led a study of intermittent cutting with UNS G43400 steel in which they tested PCBN tools (with 60% of CBN) with a ceramic phase and a ceramic tool with alumina base and reinforced with silicon carbide (Al_2O_3+SiC). The tool life results in continuous cutting were better using ceramic tools than PCBN tools. In the case of intermittent cutting, the results were closer. The wear mechanism observed in PCBN tools was flank wear due to abrasion, while in the case of ceramic tools was diffusion and abrasion in the secondary edge. Regarding the surface roughness, the better results were obtained with PCBN tools during both continuous and intermittent cutting. A great increase in surface roughness is observed when using ceramic tools as cutting time is increased.

3.4. Polycrystalline diamond

Polycrystalline diamond (PCD) is the harder known material specially recommended for cutting hard materials [49,64].

Comparisons of cemented carbides (K10) and PCD tools made by König and Erinski [65] show the better results in the case of PCD tools when machining a die cast alloy using interrupted turning. So, the tool life values of PCD tools are up to 100-times higher than in the case of cemented carbides.

Analysing continuous and interrupted turning of A390 alloy, nanoestructurated diamond coatings over tungsten carbides and PCD tools offer similar results of tool wear and surface roughness. However, during interrupted turning, the better tool wear is obtained with PCD tools in terms of flank wear [66].

4. TEMPERATURE

The importance of the temperature reached between the tool and workpiece material during machining, both in continuous and discontinuous processes, is widely recognized by researchers [67,68]. The first works identified, according to Davies *et al.* [69], are the calorimetric studies by Count Rumford. The tool temperature importance is related with tool wear, mechanics of chip formation and the promotion of plastic deformation in the machined surface. The influence of the temperature on tool wear can be seen in the work by Usui *et al.* [70], in which an equation that relates tool wear with temperature is proposed [71].

Direct temperature measurement is one of the main objectives in the temperature studies. Interest is place in getting measures of temperatures at the tool-chip interface zone and the temperatures of the chip, tool and workpiece. Besides, another objective is obtaining the temperature distribution in the tool [73].

In discontinuous cutting the temperatures are cyclical, increasing during working operations and decreasing during non-cutting periods [74]. So, differences are identified with continuous cutting, being the cutting temperature measured for discontinuous cutting lower than for continuous cutting due to the effect of non-cutting periods [9,75,76]. Besides, when the refrigeration periods are increased the maximum temperatures reached are lower. However, thermal cycles of amplitude up to 250 °C are generated in interrupted cutting [9]. Palmai [77] used an empirical formula to calculate the cyclic temperature change in interrupted cutting, studying how high speed affected the heating time to diminish the temperature rise.

Traditionally, in order to reduce the friction and temperature in machining processes cutting fluids have been used [78]. However, there are also some disadvantages associated with their use as: cost, fluid system maintenance, fluid pre-treatment/treatment/disposal, risk for employer's health or environmental impact [79-81].

Although cutting fluids are widely used in machining processes, other alternatives are being also tried in order to get more environmentally friendly operations. Among these alternatives it is possible to highlight: minimum quantity lubrication (MQL), dry machining, gaseous refrigeration, cryogenic refrigeration and solid lubricants [2,82].

4.1. Experimental measures

The main measurement techniques are widely reviewed in works as: Davies *et al.* [69], Abukhshim *et al.* [73], Silva and Wallbank [74], Barrow [83], Ay and Yang [84], Komanduri and Hou [85], O'Sullivan and Cotterell [86] and Sutter *et al.* [87]. Among the main techniques it is possible to highlight: thermocouples, infrared photography, infrared optical pyrometers, thermal paints, materials of known melting temperatures and change in microstructure with temperature in the case of high-speed steel tools [85]. The application of some of these techniques in turning processes is reported by Wanigarathne *et al.* [71].

The use of the measurements techniques is also done during discontinuous cutting. In particular, the use of thermocouples in interrupted cutting/milling has been done by researchers such as Lezanski and Shaw [88], Narutaki *et al.* [89] or Stephenson and Al [75] in their works [69].

Kitagawa *et al.* [90] used thermocouples to measure temperature during intermittent turning of a titanium disk. A micro-thermocouple is embedded in the tool to measure temperature.

Thermocouples have been also used by Jiang *et al.* [72] in their study of interrupted cutting. The experimental measurements show that the maximum temperature is reached when using 1500 m/min as cutting speed. Increasing the cutting speed over that value leads to a decrease in the maximum temperature reached.

The use of embedded thermocouples to measure temperatures in interrupted cutting is done in the investigation by El-Bestawi *et al.* [91]. In their work, the measured temperatures varied between 300 °C and 350 °C in the case of interrupted cutting, while for continuous cutting are higher (between 350 °C and 500 °C).

Another experimental technique is used by Armendia *et al.* [9]. In their work, researchers used a micro-thermal imaging to measure the temperature during interrupted cutting of titanium alloy Ti6Al4V and AISI 4140. The experimental measurements show how tool temperatures during interrupted cutting vary considering the point of the tool chosen. Highest temperatures are measured on the edge of the tool.

4.2. Temperature prediction

The experimental measurement using experimental techniques at the tool–chip–workpiece interface is very difficult due to the cutting movement and the small contact areas involved. Due to these difficulties, another strategies to estimate the temperature in cutting processes are used [92]. Arrazola *et al.* [1] classify the main methods to predict temperature fields in: analytical thermal modelling, combined slip-line and analytical thermal modelling, finite difference methods (FDM) and finite element methods (FEM). These methods can be classified, in a more simplified way, into: analytical and numerical methods [73] that are widely analysed and reviewed in the literature, mainly in the case of continuous processes. Following, an overview of the main analytical and numerical methods is given, focusing on the application of these methods in discontinuous cutting processes.

Analytical methods

Analytical models to predict temperatures have been investigated in the last decades. Some of the first models include the works of Trigger and Chao [93] and Loewen and Shaw [94] that are summarized in Table 3 among other works.

Regarding discontinuous cutting, Chakraverti *et al.* [95] presented a temperature model for the a four-slot workpiece in intermittent turning. The study uses a one-dimensional (1D) model for temperature distribution in the tool. The tool is considered a semi-infinite body heated periodically over its surface by a rectangular heat flux. The temperature at a position X and for a generic time t can be evaluated by using the next equation and its boundary conditions:

$$\frac{\partial\theta}{\partial t} = \alpha \times \frac{\partial^2\theta}{\partial X^2}, \tag{1}$$

Taken as initial point the above equation, the authors reach a final equation to calculate temperatures (θ) depending on position (X) and time (t).

Another analytical work that considers the case of discontinuous cutting is presented by Radulescu and Kapoor [96]. The model can be applied to any continuous or interrupted three-dimensional (3D) cutting process to predict temperatures of the tool by using both energy balance and heat transfer analysis, and the cutting forces as input. The results of the research indicate that the tool-chip interface temperature increases with cutting speed in both continuous and interrupted cutting.

From their side, Stephenson *et al.* [97] presented a model to predict the tool temperatures in contour turning under transient conditions that allows reducing the computing time and simplifying the input requirements. The heat flux was determined from the measured cutting forces using Loewen and Show's [94] model. In general, the predictions obtained with the ambient temperature boundary condition at the bottom of the insert were found to agree well with the measured temperatures [73,98].

Kountanya [76] studies the transient tool temperatures in interrupted cutting. The initial focus was the feed-direction modulated turning. Here, the instantaneous uncut chip thickness (IUCT) was modelled including the regenerative effect introduced by the modulation.

The model identifies the cutting tool with a one-eighth semi-infinite space and uses the heat-conduction equation (Eq. (2)), for constant thermal properties.

$$\frac{1}{\kappa} \times \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} + \frac{\partial^2 T}{\partial Z^2} + \frac{q'}{k}. \tag{2}$$

Table 3. Main works on analytical methods.

Works
Trigger and Chao [93], Loewen and Shaw [94], Chao and Trigger [99], Rapier [100], Weiner [101], Boothroyd [102], Wright *et al.* [103], Chakraverti *et al.* [95], Venuvinod and Lau [103], Radulescu and Kapoor [96], Young and Chou [105], Stephenson *et al.* [97], Komanduri and Hou [106], Zhang and Liu [107], Kountanya [76], Shijun and Zhanqiang [108] and Jiang *et al.* [72].

Last equation is solved using the Green's function solution reaching the next equation for the temperature:

$$T_{GR}(x,y,z,t,\tau)=\left(\frac{q}{\rho\times c_p}\right)\int_0^{l(t)}\left[\int_0^{\omega}F_{GR}(x,\xi,y,z,\zeta,t,\tau)\,\mathrm{d}\zeta\right]\mathrm{d}\xi. \tag{3}$$

The temperature model is validated with data from Stephenson and Ali [75] and with a simple FEM analysis for steady-state cutting without modulation.

A work on interrupted cutting is done by Jiang *et al.* [72], analysing a milling case. The tool temperature field is calculated using a time varying heat flux flowing into cutting tool inserts. Moreover, the transient temperature on the workpiece is also calculated. The main equation that represents the tool temperature model is the next:

$$T(x,y,z,t)=\frac{\alpha_{tool}}{\kappa_{tool}}\int_0^{t}\theta_{GR}\left(x,y,z,t,cf_z\sin\left(\frac{\tau_1}{\tau}\times\omega_c\right),L_y,0,D\right)\times q_{toolm}\times\frac{\sin\left(\frac{\tau_1}{\tau}\times\omega_c\right)}{\sin\omega_c}\times\mathrm{d}\tau. \tag{4}$$

The model proposed by Jiang *et al.* [72] let see the predicted influence of non-cutting times for four types of processes with cutting time/non-cutting time relations between 1/19 and 1/5. In the work, it is possible to see that increasing non-cutting time decreases the temperature profile.

Numerical methods

Numerical methods are another different strategy to analyse temperatures during machining processes. The main numerical methods include FEM and FDM. These methods have been applied to simulate the tool-chip interface temperature [109].

Finite element simulations have been successfully applied for modelling orthogonal metal cutting processes. They have significantly reduced the simplifying assumptions of the analytical models. However, the use of FEM in metal cutting research requires a large number of input parameters that limits the utilization of the method [73,110]. Another approach to numerical methods is by using FDM. However, the method cannot directly determine the quantitative cutting temperature because the heat flux at tool-chip interface is not known precisely [109]. Both methods have been widely used in temperate prediction. Other numerical methods can be cited as the boundary element method (BEM). BEM has been applied in metal cutting processes by researchers as Chan and Chandra [111], Chen *et al.* [112] and Du *et al.* [113]. Several applications of these methods are summarized in Table 4.

Kitagawa *et al.* [90] developed a numerical method to verify the measures done with experimental techniques. In particular, the numerical method is used to analyse an intermittent cutting process. The model takes as main equation the governing equation (Eq.(5)) for heat transfer. Then, the equation is discretized using the FDM.

Table 4. Main works on numerical methods.

Method	Work
Finite element method	Tay *et al.* [114-115], Muraka *et al.* [116], Stevenson *et al.* [117], Dawson and Malkin [118], Kim and Sin [119], Ceretti *et al.* [120], Strenkowski *et al.* [121], Moriwaki *et al.* [122], Lei *et al.* [123], Liu and Guo [124], Shet and Deng [125], Davies *et al.* [126], Ren *et al.* [127], Abukhshim *et al.* [128], Chiou *et al.* [98], Brandão *et al*. [129] and Akbar *et al.* [130].
Finite difference method	Boothroyd [131], Levy *et al.* [132], Usui *et al.* [70], Smith and Armarego [133], Kitagawa *et al.* [90], Lazoglu and Altintas [68], Ulutan *et al.* [134], Pombo *et al.* [135] and Liang *et al.* [109].
Boundary element method	Chan and Chandra [111], Chen *et al.* [112] and Du *et al.* [113].

$$\frac{\partial\theta}{\partial t} = k \times \nabla^2\theta - \vec{V} \times \nabla\theta + \frac{q}{\rho \times C}. \quad (5)$$

The numerical model let compare the experimental measured results with the predicted ones. Thus, the evolution of the temperature in the cases of continuous and intermittent turning, for both dry machining and wet machining let see how in intermittent turning the maximum temperature is lower than the one obtained in the continuous case [90].

Another numerical model that deals with discontinuous cutting processes is the one presented by Lazoglu and Altintas [68]. Their model predicts the temperature in the cutting zone in continuous and discontinuous cutting. The work uses the first law of thermodynamics to develop a numerical model based on the FDM. The model allows predicting the steady-state tool and chip temperature fields and the transient temperature variation in continuous and interrupted orthogonal cutting with varying chip load, such as in milling.

The heat balance equations are determined in partial differential equation for the chip and for the tool. To solve the steady-state for tool and chip temperature fields the FDM is used. Besides, in order to determine the transient temperature variation in the case of interrupted cutting, the chip thickness is discretized along the time. By knowing the steady-state temperature and time constants of the discretized first order heat transfer system, an algorithm is presented to determine the transient temperature variations in interrupted turning and milling operations.

4.3. Cooling/lubricating

The influence of the cooling/lubricating systems is widely studied in the literature and a lot of experimental research is done using different systems. Mainly, due to the need to obtain greener processes. However, less investigation is done in discontinuous cutting. Following, some of the main studies are highlighted acknowledging the influence of cooling/lubricating systems in discontinuous cutting.

Dry and wet systems are investigated in the work by Kitagawa *et al.* [90]. In their study, the temperatures are measured by means of thermocouples, identifying how the temperatures are slightly lower when using wet conditions.

Another work on discontinuous cutting is done by Itoigawa *et al.* [136]. Their research is focused on the study of the MQL system during the intermittent turning of an aluminium alloy. As cutting fluid two types of lubricant are employed; one is paraffinic mineral oil without additives and another is refined vegetable oil, which mainly consists of a triol-ester with large polarity.

When using the ester-type lubricant, the cutting force is suppressed to a low level at the initial stage of the cutting intervals. This initial reduction may result in low cutting force in an MQL intermittent cutting. Moreover, another conclusion of the study is that the larger the cutting interval between cut in intermittent cutting, the lower the effect of lubricant on the cutting force. This is due to the lubrication effect of the lubricant film on a tool decreases with the increase in the sliding length.

The work of Rubio *et al.* [8] also assesses the use of the MQL systems during intermittent turning. In this case, the research is focused on the intermittent turning of a magnesium alloy using both dry machining and the MQL system. Their work show how the cooling/lubricating system employed has a significant influence on the surface roughness. Moreover, a moderate beneficial effect on surface roughness is seen when using a minimum quantity of lubricant in the MQL system.

The use of the cryogenic refrigeration was investigated by Yong *et al.* [137]. Specifically, the work studies the influence of cryogenic treatments on carbide tools during interrupted turning. The results show that the use of cryogenical treatment let achieve better results when analysing flank wear. Gill *et al.* [138] also analysed the use of cryogenically treated carbide inserts, identifying a better performance when using cryogenical treatment in terms of tool wear. Besides, an important influence of the cutting conditions is identified in the experimentations.

Finally, the investigation by Junior *et al.* [139] evaluates the influence of different cooling/lubricating during interrupted cutting of a stainless steel. The obtained results let see the influence of the system chosen in terms of tool life. So, the better results are obtained with wet machining with vegetal oil, then the best performance is obtained with the MQL system with vegetal oil, then dry machining and, finally, with wet machining with a vegetal oil emulsion. In conclusion, the authors identify a higher influence of the lubricant capacity than of the cooling capacity.

5. CONCLUSIONS

The constant knocking between the tool and the workpiece and the thermal cycles are the main characteristics of discontinuous cutting processes. These characteristics make needed to analyse specifically these machining processes.

The present work shows a review on discontinuous cutting addressing the following points:
- The tool failure mechanisms are one of the main points studied in the literature. In this way, the following failure mechanisms are highlighted: thermal cracks, mechanical impacts, adhesion mechanisms, negative shear angle, incipient chip deformation or a combination of different mechanisms.
- Due to the difficult conditions of discontinuous cutting, the selection of the tool material is a critical issue to deal with. In the present research several works have been reviewed analysing the use of different kinds of tool materials. In particular, carbides, CBN, ceramic and PCD tools have been reviewed.
- The thermal effects are also one of the points that attract the interest of researchers. In this way, different strategies to study temperature are highlighted. For instance, direct temperature measurement and analytical and numerical methods for temperature prediction. Another strategy to diminish the effects of the temperature is the use of different cooling/lubricating systems. Some examples of the application of different cooling/lubricating systems are provided in the present work.

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