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Performance analysis of new external chip breaker for efficient machining of Inconel 718 and optimization of the cutting parameters

Bahattin Yılmaz[a], Şener Karabulut[b,*], Abdulkadir Güllü[a]

[a] Department of Manufacturing Engineering, Gazi University, 06500 Ankara, Turkey
[b] Department of Mechanical Program, Hacettepe University, 06935 Ankara, Turkey

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ABSTRACT

Chip control issues are common problems in finishing, semi-finishing, and machining with variable depths of cut in the turning operations of ductile steels and super alloys. Most inserts have chip breaker geometry to control chips in the turning process. However, unbroken chips still cause obstacles for automation and production management in the machining of ductile materials. In this study, a new cutting tool holder with an external chip control system was designed to break continuous chips, and the effect of the holder was examined with respect to the efficient machining of Inconel 718. The efficiency of the developed chip breaking system was investigated relative to different feed rates, machining speeds, and cutting depth by using cementite carbide inserts under dry cutting conditions. The studies were performed based on the Taguchi L_{16} design of experiments using a standard tool holder and a newly developed tool holder with a chip breaker. The surface quality, cutting force characteristics, temperature behaviors, and wear mechanisms of the inserts were measured to elucidate the influence of the chip breaking system on the machining process. Excellent chip breakability was achieved with respect to all the examined cutting parameters and chip morphologies. A remarkable improvement in tool wear was observed with the use of the chip breaker system for cutting parameters including a high machining speed, a low feed rate, and cutting depth combinations. Cutting forces and temperatures slightly decreased, and surface quality improved with increases in the cutting speed during external chip breaker-assisted turning of Inconel 718. The results indicated that the regression models of experimental responses were statistically significant.

1. Introduction

Safety and automation are extremely important requirements in manufacturing processes. Continuous chip formation during a turning operation has a negative effect on machine and operator safety, workpiece surface quality, operation continuity, and efficiency. Long continuous chips are typically formed in the turning of ductile materials at a high machining speed, low feed rate, and low cutting depth resulting in a good surface finish. However, long chips can result in issues related to chip disposal and high local temperatures based on the contact area between the chip and cutting tool. Hence, continuous chip formation is not desirable for effective machining operations, process reliability, and surface roughness. Inconel 718 is a nickel-based alloy and is classified as a hard-to-machine material. It is commonly used in aerospace industries, nuclear reactors, gas turbines, petrochemical devices, and submarines owing to its attractive superior properties such as high mechanical strength and high corrosion resistance. Despite the aforementioned superior properties, the machinability of Inconel 718 continues to pose a challenge owing to factors including high temperatures, tendency to display a built-up edge (BUE) formation, strong work hardening, and inefficient chip fracturing behavior. These undesirable parameters cause to higher mechanical loads, and high cutting temperatures at the chip-tool interface result in increased tool wear, reduced productivity, reduced process reliability, and increased surface roughness [1–5]. Therefore, numerous experimental studies examined the machinability of Inconel 718 and ductile steels using specially designed chip breakers and high pressure jets (HPJ). Kim and Kweun [6] proposed a special chip breaking system to fracture continuous chips in the turning of ductile steel, and the results indicated that long chips could be broken at cutting speeds below 150 m/min. Güllü and Karabulut [7] developed a dynamic chip breaker system to break long chips while turning Inconel 718, and the findings revealed that continuous chips could be broken in all cutting conditions using a dynamic chip breaker. The authors reported that the surface roughness values and cutting temperatures decreased with the use of the chip breaker system. Ezugwu [3] suggested that the primary objective of a machining technique under high pressure involves decreasing the cutting temperatures in the machining environment and achieving high chip

* Corresponding author.
E-mail address: senerkarabulut@hacettepe.edu.tr (Ş. Karabulut).

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breakability. The study reported that a high pressure coolant (HPC) could effectively decrease the cutting temperatures during the high speed turning of Inconel 718. In the study, tool life improved, and short, continuous tubular chips were formed in the machining of Inconel 718 under a coolant pressure up to 150 bar. Smaller arc shaped chips were obtained during machining with an increased coolant supply pressure corresponding to 203 bar. Ezugwu and Bonney [8] investigated the surface roughness, tool wear, and cutting forces in the high-pressure, assisted machining of Inconel 718 with physical vapor deposition (PVD) coated carbide inserts. They reported that suitable surface quality and increased tool performance were obtained when turning Inconel 718 at a high coolant pressure. Chip breakability depended on the cutting parameters, and the chip did not break with lower coolant pressures during the machining of Inconel 718. Courbon et al. [9] studied the influence of a high-pressure jet cooling system on chip breakability, cutting forces, cutting temperatures, and surface quality in the machining of Inconel 718 using coated carbide cutting tools. The turning processes were performed at various jet pressures, cutting speeds, and feed rates. They observed that the high-pressure jet system ensured enhanced chip breakability and reduction in BUE and machining forces. Çolak [10] studied the influence of conventional machining and high-pressure jet cooling machining on cutting tool performance and machining forces in the finishing turning of Inconel 718 using coated carbide tools. The study indicated that HPC had a considerable beneficial effect on cutting tool wear and provided the desired chip breakability at a pressure of 300 bar. Alagan et al. [11] studied the influence of forced coolant application on tool wear using a modified cutting insert with an extra groove designed to enhance the effect of the coolant at the tool-chip interface. The findings revealed that the modified cutting tool demonstrated an improvement in tool life that approximately corresponded to 24–33%. Bermingham et al. [12] investigated the effectiveness of a cryogenic coolant on tool wear, machining forces, and chip morphology during the turning of Ti-6Al-4V. The results indicated that a remarkable improvement in tool performance prevented heat generation during the machining process. Additionally, a long serrated chip formation was produced, the main cutting force was reduced, and the thrust force increased in the machining of Ti-6Al-4V with the introduction of a cryogenic coolant. Palanisamy et al. [13] studied the effect of HPC on chip formation in the machining of Ti-6Al-4V. The findings suggested longer tool life, better surface roughness, and smaller chips were obtained with the application of a high-pressure coolant. Khan et al. [14] investigated the influence of a pressurized coolant on forces, temperatures, and chip production in the turning of Ti-6Al-4V. The experimental results showed that high pressurized cooling and lubrication improved the cutting forces, temperatures, chip breakability, and machining performance. They also observed that chip breakability was not achieved at a low pressure of the applied coolant. Mia and Dhar [15] studied the influence of a HPC on the surface finish in turning hardened EN 24T steel and developed a prediction model for surface roughness using artificial neural networks. Lorentzon and Jarvstrat [16] indicated that tool wear was a severe problem in the machining of Inconel 718. They investigated an empirical tool life model in finite element chip formation simulation to estimate tool wear of a cemented carbide tool in the machining of Inconel 718, and the results indicated good agreement between experiment and finite element simulation. Cantero et al. [4] investigated tool wear behaviors during the turning of Inconel 718 with finish machining variables under dry and wet cutting environments. They observed the notch wear mode in all cutting conditions, and the observations indicated that cutting tool life diminished in 2 min at the increased cutting speed of 70 m/min due to strong chipping. Tebaldo et al. [17] studied the effect of different cutting conditions and cooling systems on tool life and surface quality in the machining of Inconel 718 using a cemented carbide insert. The results showed that tool life was not significantly affected by the varying coolant system, and lowest surface roughness values were observed under a wet and eco-friendly minimum quantity cooling system in the turning process. Sutter and Ranc [18] examined the type of chip formation and cutting temperatures generated during the machining of low alloyed medium carbon steel (42CrMo4) and low carbon steel (C15). They observed that maximum temperatures were generated near the tool-chip interface and that the temperature in the chip increased with the increases in the machining speed. Shokrani et al [19] stated that the chip breaker mechanism and cutting inserts having with chip breakers are mostly used to enhance the chip breakability. However, the influence of the chip breaker is inadequate in machining ductile materials. Hong et al. [20] used a cryogenic coolant in machining AISI 1008 low carbon steel to improve the chip breakability. Lotfi et al [21] investigated the influence of chip breaker geometry on cutting force and chip shape in machining AISI 1045 steel. They found that the cutting force was affected by the chip breaker geometry. In another study, Gurbuz et al. [22,23] stated that the cutting force was increased with the complexity of the chip breaker geometry in machining of AISI 1050 steel. They developed a prediction model using the length and angles of the chip breaker on the cutting forces. Jawahir [24] investigated the mechanisms of chip breaking and chip flow during the machining, and stated that the optimum cutting tool performance will obtain depending on the chip breakability and the restricted chip contact. Smith et al. [25,26] used the oscillating CNC toolpaths to break the long chips and investigated the effects of the oscillating toolpaths on the cutting temperatures during turning process of the 304 stainless steel. They reported that the temperatures were lower in machining with oscillating toolpaths than in conventional cutting under the same machining conditions. The cutting tool wear was reduced with the decreasing cutting temperature and the machine tool was affected from the cutting conditions to perform the oscillating toolpaths. In another study, Smith et al. [27] described a computer simulation to predict chip size and surface roughness determined the cutting parameters based on the oscillating cutting tool paths. They observed that the surface finish was more sensitive to oscillation amplitude and the experimental measurements and simulation results showed a good agreement.

Thus, extant studies that focused on the machining of Inconel 718 and super alloys revealed the importance of chip breakability and temperature reduction in the cutting environment. Both the aforementioned machining problems lead to a reduction in tool life owing to increased cutting temperatures at the tool-chip interfaces. Most previous studies examined the effect of a high-pressure coolant to obtain efficient chip breakability, lower temperatures, better surface finish, and improved tool life in the machining of nickel-based super alloys. The main objective of this machining technique involved solving the chip breaking problem and reducing the friction between the chip and cutting tool during the turning of super alloys and ductile materials. In a previous study [7], Güllü and Karabulut focused on a dynamic chip breaker system to break long chips and used on the conventional lathe machine efficiently. On the other hand, it was not practical for the CNC turning machine due to the tool-changing problem. In this new version, it was designed a smaller apparatus including a special gearbox to transfer the motion from the DC motor to chip breaker and empowering the tool changing in CNC lathe. The chip morphology, tool wear behavior, cutting forces, temperatures between the tool-chip interface, and surface roughness were investigated in conventional machining as well as in chip breaker-assisted machining of Inconel 718. The machining experiments were performed using fine cutting parameters based on the Taguchi L_{16} design of experiments. Furthermore, the test results were analyzed using ANOVA, and ideal machining variables were determined from the statistical analysis of all the responses.

2. Experimental procedures

2.1. Chip breaker design

In the continuous turning process of ductile steels and super alloys, the removal of chips in the machining environment is an important factor for automation, productivity, and operator safety. A considerable amount of the cutting temperature generated in the cutting area is also removed with the chips and transferred to the cutting insert and workpiece based on the chip formation. The unbroken chips often wrap around tools and the workpiece resulting in tool breakage due to increasing temperatures and re-cutting of a trapped chip. The hot chip affects workpiece tolerances, tool life, performance of the insert, machining time, and operator safety. Therefore, the chip breaker design criteria are intended to break long ductile chips in all cutting conditions and reduce the harmful effects of the long chips on the cutting tool, workpiece and process efficiency. To improve the machining performance of Inconel 718, an external apparatus was developed to break and quickly remove long chips from the cutting zone in the continuous turning process. For this reason, T groove milling cutter form was taken as an example to break the chips applying impact and force and a special chip breaker was designed using the design software SolidWorks. Then, it was fabricated by a wire electro-discharge machine. A standard cutting tool holder was then drilled from the bottom side and mounted on a DC motor having with different revolutions. DC motor was actuated by a three-stage (1.5 V, 3–3.5 V and 6–8 V) low voltage power supply and the motion was transferred from DC motor to the chip breaker using a specially designed gearbox. It was observed that the long chips were not broken at lower revolutions of the breaker and jammed between the workpiece and chip breaker. The chip breaker was acted like a milling cutter and quickly removed the broken chips from the cutting zone at speed of 9000 rpm. Hence, highest revolution of the DC motor was used and 9000 rpm was obtained at 6–8 voltage of the power supply. The external chip breaker system was assembled on the tool holder with a 1 mm clearance between the breaker and cutting tool (Fig. 1). The cutting tool was easily mounted and unmounted in the required time frame, and the chip breaker system did not cause any obstacles in the machining environment during the turning process.

2.2. Machining setup and cutting parameters

Turning operations were performed on a Johnford TC35 CNC turning machine with a maximum spindle speed and maximum spindle motor power corresponding to 6000 rpm and 10 kW, respectively. The feed rate, cutting speed and cutting depth corresponded to the turning variables for the investigation to determine the effect of the chip breaker system on breakability, surface quality, machining force, cutting temperatures, and tool life. The chemical compositions and mechanical properties of the workpiece are listed in Tables 1 and Table 2 (from supplier), respectively. The experimental workpiece was provided in the form of a cylindrical rod with a diameter of 50 mm and a length of 400 mm for the turning experiments. The tests were conducted using a standard tool holder and the developed tool holder with an external chip breaking system under a dry machining environment (Fig. 2). Additionally, PVD TiAlN-TiN coated positive cemented carbide square inserts with a clearance angle of 7° with the ISO designation "SCMT 120408" were used for the chip removal experiments and mounted on an SSBCR 2525M 12 positive tool holder (with a lead angle of 75°) that was produced by Sandvik Coromant. The cutting force

Table 1
Chemical composition of Inconel 718 (wt %).

C	Mn	Si	Co	Al	Ti	Mo	Cb + a	Fe	Cr	Ni
0.020	0.04	0.06	0.23	0.56	0.98	3.04	5.34	18.40	17.83	53.53

Table 2
Mechanical properties of the experimental specimens.

Hardness (HB)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (5%)
388	1375	1170	23.3

measurements were performed using a three-component piezoelectric dynamometer Kistler 9257A with an appropriate multi-channel charge amplifier (Kistler 5019). Cutting force values were stored on the computer and monitored during the experiment using Dynoware 2825Ai-2, a data acquisition software. A Raytek MI3 2M digital pyrometer was utilized for continuous noncontact temperature monitoring in the turning process. The MI3 infrared temperature sensor head was precisely installed on the turret at a distance of 30 cm from the cutting tool rake face and connected to the computer with USB digital communication (Table 3). The temperature of the tool-chip interface was continuously monitored via contactless infrared temperature measurements during the experiments. The technical and measurement specifications are listed in Table 4. The surface quality of the machined part was measured using the Mahr M1 perthometer, a portable surface finish measurement instrument (with a cut-off distance of 2.5 mm). The calibration of the surface roughness instrument was performed using a standard calibration part prior to the measurements. The cutting insert and chips were evaluated by scanning electron microscopy (SEM, JEOL JSM 6060 LW) to observe the influence of the chip breaker system on a BUE creation with respect to the cutting surface of the insert and chip formation. All measured values for machining force, cutting temperatures, and surface roughness were evaluated and depicted on mean effect graphs by using Minitab statistical software.

2.3. Experimental design

In the experimental study, the Taguchi L_{16} orthogonal experimental design was employed to decrease the number of experiments and to define the optimal turning variables for the machining of Inconel 718. Conventional machining and external chip breaker-assisted machining were carried out in the experiments and involved investigating the effect of the chip breaking system and cutting parameters on the machining force (Ft), cutting temperature (C_T), surface roughness ($R_{a,}$), and cutting tool performance. The experimental cutting variables were determined based on the ISO standard 3685, cutting-tool-manufacturer suggestions, and previous studies [7,28]. Each cutting experiment has been performed three times with a fresh cutting edge under the same cutting conditions. The feed rate, cutting speed, and cutting depth were selected as the machining factors with four levels corresponding to each

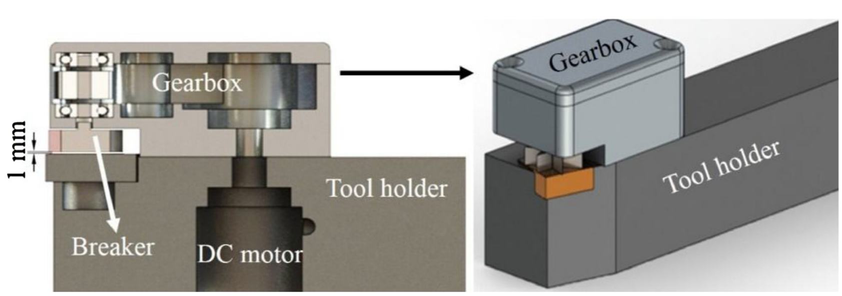

Fig. 1. Overview of the external chip breaker system.

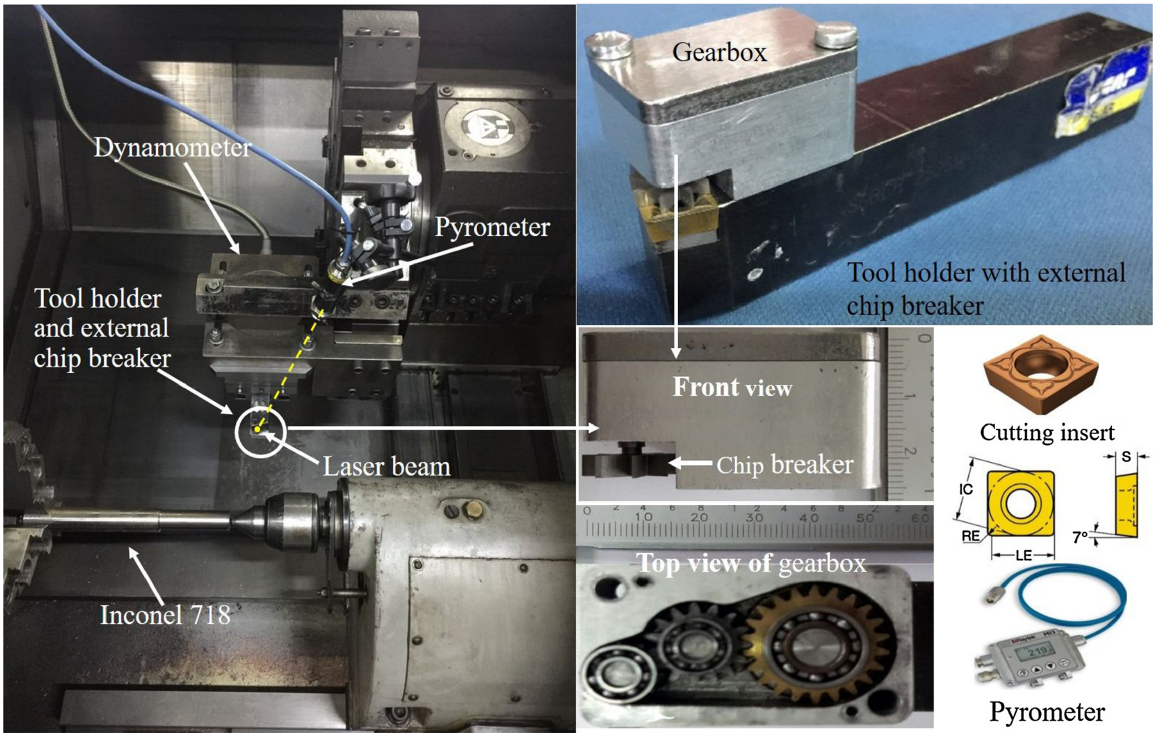

Fig. 2. Overview of the experimental setup in the external chip breaker-assisted turning operation.

Table 3
Measurement and technical specification of the pyrometer sensing head used in the tests.

Factors	Technical specification
Temperature range	250–1400 °C
Spectral response	1.6 µm
Optical resolution	100:1
Response Time	10 ms
Accuracy	± (0.5% of reading + 2 °C)
Repeatability	± 0.25% of reading + 1 °C
Temperature coefficient	0.01% of reading/K
Emissivity	0.100–1.100
Transmission	0.100–1.100
Loop Time	4 ms

Table 4
Cutting conditions and experiment levels.

Factors	Level 1	Level 2	Level 3	Level 4
$A-$ Machining speed V_c (m/min)	25	35	50	70
$B-$ Cutting feed fz (mm/rev)	0.10	0.13	0.17	0.22
$C-$ Cutting depth a_p (mm)	0.8	1.0	1.3	1.7
Machining environment		Dry		

factor under a dry cutting environment as given in Table 4.

3. Results and discussion

3.1. Chip formation and cutting tool performance

In the study, it was observed that there were variations in chip breaking ranging from hard to almost impossible to break long chips that were based on the machining variables used in the tests as shown in Fig. 3(a) and (c). The chips formed in the turning experiments were collected to evaluate the cutting conditions and chip breaker performance. Most of the cutting inserts contained hundreds of chip breaker geometries in the rake face to control and break the long snarled chips produced during the turning of ductile metals. Despite the chip breaker geometries, it was not possible for the cutting inserts to break the continuous chips in the turning of ductile steels and super alloys. The feed rate and the maximum chip thickness are directly related, and the feed rate and the shear plane angle are inversely related. With respect to higher feed rates, the shear plane angle reduces with increases in the chip thickness. Conversely, with respect to higher feed rates, the chip breaking performance increases with increases in the chip thickness. The initial chip flow angle that affects the chip width depends on the depth of cut, and thus the bending resistance of the chip increases with increases in the depth of cut. In most cases, increases in cutting depth improve the ease of breaking the chip owing to the applied torsional strain. In addition to the cutting feed and cutting depth, the machining speed also affects the chip breakability based on the altering size and form of the chip removing zone. An increased cutting speed leads to thinner chips and decreases the thickness of the chip owing to the reduced cutting area. Therefore, chip breakability reduces with decreases in the chip thickness and insufficient strain of a thin chip [6]. Thus, the tendency of chip breaking improves when a cutting combination with increased cutting feeds, increased cutting depths, and decreased cutting speeds is used. However, these cutting conditions lead to poor surface quality and tool life.

It is extremely difficult to achieve efficient chip breaking in finishing and semi-finishing cutting conditions using available insert geometries in the turning of Inconel 718 super alloy. Hence, a special chip breaker apparatus was designed to control the chip formation and break long chips. The principle of the developed external chip breaker was based on the production of fractures by the impact energy and force acting on the chip surface. Therefore, continuous chips in the machining of Inconel 718 were efficiently broken in all the cutting conditions by using the tool holder with an external chip breaker. Fig. 3(b) and (d) indicate the performance of the developed chip breaking system at an increased cutting speed, reduced feed rate, and reduced cutting depth in the turning process. It was observed that unbroken long snarled and tubular chip formations were obtained based on the cutting conditions (Fig. 3(a) and (c)). Tubular chips with continuous flow were

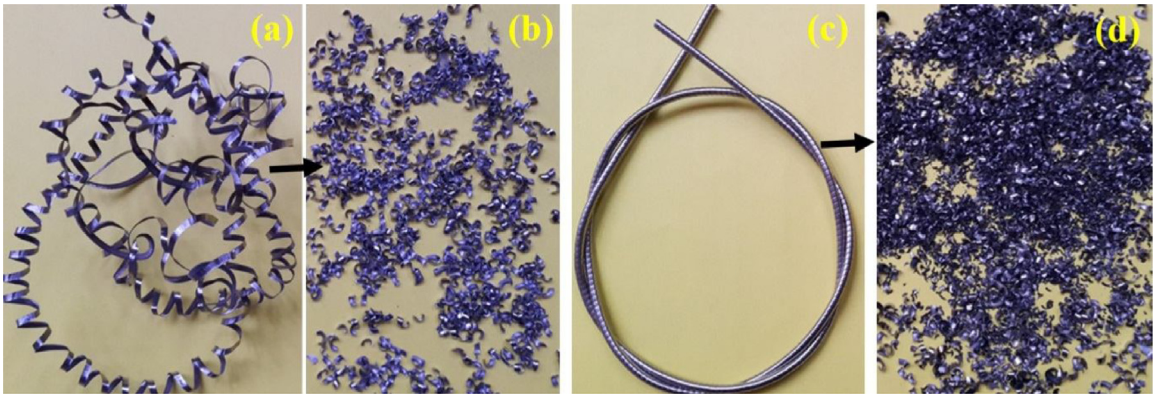

Fig. 3. Various chip formations at different machining conditions in conventional (a,c) and external chip breaker-assisted (b, d) machining: (a, b) *at* $V_c = 50\,m/min$, $fz = 0.22\,mm/rev$ and $a_p = 1.0\,mm$ and (c, d) *at* $V_c = 70\,m/min$, $fz = 0.10\,mm/rev$, and $a_p = 1.7\,mm$.

passed over the rake face of the cutting insert with a constant contact that transferred the cutting heat to the insert. These types of chips were produced at a high cutting speed and lower feed rates. Better surface values were obtained when these types of chips were formed albeit the insert was rapidly worn. Conversely, long snarled spiral chips were wrapped around the tool and workpiece causing downtime. The chip formation increased the temperature in the cutting environment, and in some cases, an additional attempt was made to use the cutting tool to cut the trapped chip between the workpiece and the tool. As a result of the aforementioned cutting phenomena, the tool life decreased, and this resulted in BUE formation, chipping, cutting edge breakage, and notching on the rake face of the tool that was close to the cutting edge during machining with the standard cutting tool.

Fig. 4 shows high-magnification SEM micrographs of chips with a deep saw-tooth during the machining of Inconel 718 by using an external chip breaker. Chip formations are affected by the cutting parameters, and the chip breaker changes the mechanism of the chip formation to serrated and saw-toothed mechanisms. As shown in Fig. 4(a) and (b), highly localized shear flow forms were observed outside the broken segmented chips, and this resulted in a rough surface due to adiabatic high shear strain, extreme pressure, high temperatures, and high cutting friction at the tool-chip interface in the primary cutting zone at low cutting feeds, machining speeds, and depths of cut. The rough surface and deep saw-tooth could be related to the heat generated between the cutting tool rake face and chip at the secondary shear zone due to the friction that resulted in the further deformation of the

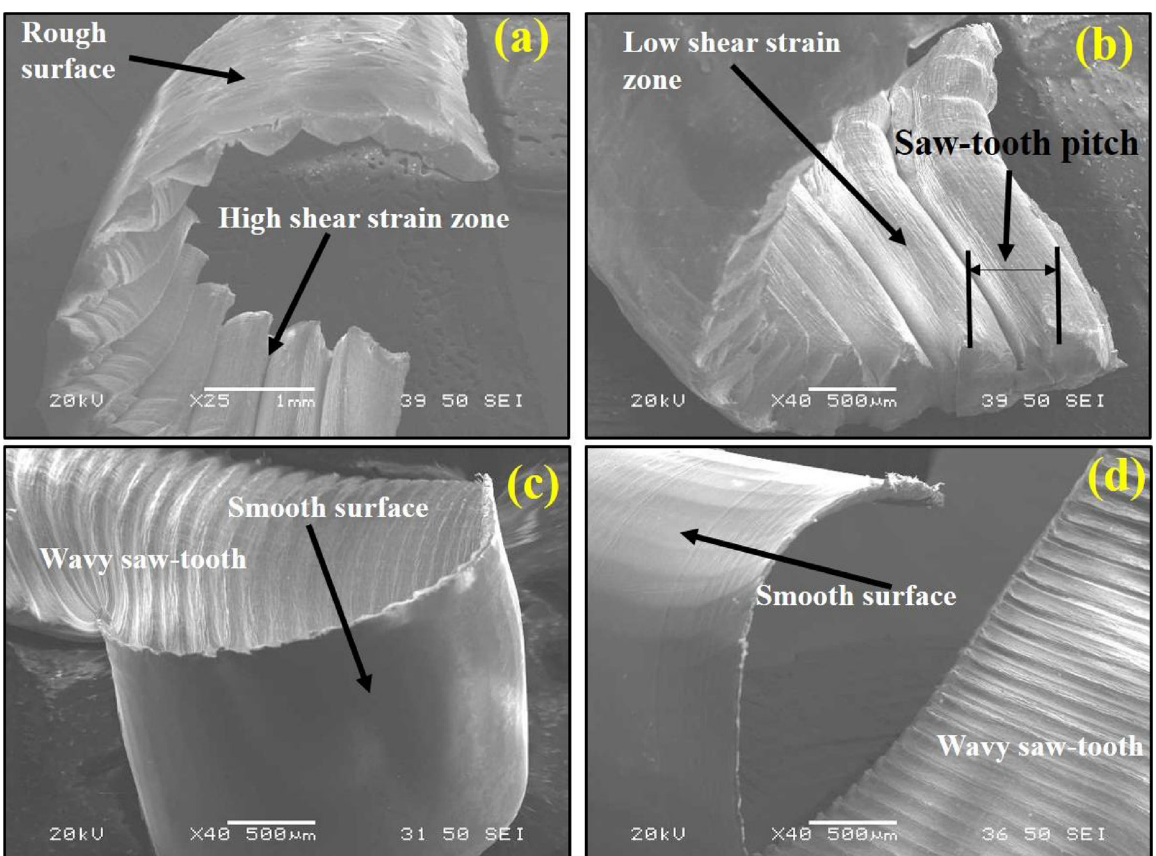

Fig. 4. SEM micrographs of broken chips produced in the chip breaker-assisted machining: (a,b) at $V_c = 25\,m/min$, $fz = 0.22\,mm/rev$, and $a_p = 1.7\,mm$ *, (c,d) at* $V_c = 70\,m/min$, $fz = 0.13\,mm/rev$, and $a_p = 1.3\,mm$.

chip material and strain energy released during the quick chip breakage. Serrated chip formations with small and wavy saw-tooth and better surface finishes were achieved in the turning of Inconel 718 at high cutting speeds and relatively low feed rates and depths as shown in Fig. 4(c) and (d). With increases in the machining speed, the chip shapes are transformed from the saw-toothed type to the wavy type, and the chip radius also increases [29]. It is inferred that the surface quality of the finished part and the worn status of the cutting tool corresponds to a reflection of the workpiece. In Fig. 4(a), the chip has a rough surface and may retain some of its layers on the cutting edge or over the machined surface of the workpiece material as a BUE. As shown in the SEM micrograph, the finished surface quality of the workpiece worsened during the study. As shown in Fig. 4(c) and (d), the chips exhibit a smooth and better surface, and thus it is concluded that the machined surface of the workpiece possesses an acceptable surface roughness. The chip morphology and quality of the chip surface are influenced by the external chip breaker and cutting conditions during the turning of Inconel 718.

In the study, the influence of the chip breaker on the tool wear mechanism and the cutting tool behavior was evaluated for a cutting time corresponding to 4 min using SEM and optical microscopy. The cutting insert wear formations are depicted in Fig. 5(a) and (c), when using a standard tool holder without a chip breaker. Fracture of the cutting tool edge and notch wear are observed during the turning process under high feed rates, machining speeds and depths of cut. Additionally, BUE formation was observed on the rake face of the insert at low cutting speeds. These wear formations could have caused high localized cutting temperatures, high pressure, and high friction at the tool chip interference in the machining area. Furthermore, cutting tool breakage could be related to the excessive amount of adhered materials and notch wear. The notch wear rapidly increased at lower cutting speeds and reduced the tool life. As shown in Fig. 5(b) and (d), the cutting tool wear behaviors under different cutting conditions were examined using an external chip breaker during the experiments. It was observed that the developed chip breaker exerted a positive effect on tool life. A small amount of welded materials and burr associated with BUE and small breakages and flank wear mechanisms were observed during the machining experiments that were conducted with an external chip breaker. Tool breakage and BUE modes were observed at lower feed rates and cutting speeds. However, the edge breakages did not progress to the end of the tool life. A comparison between conventional machining and chip breaker-assisted machining indicated the advantages of the external chip breaker. The SEM micrographs indicated that the tool life in the case of the tool holder with an external chip breaker exceeded that when a standard tool holder was used. This could be related to the fact that the external chip breaker quickly removed the long chips from the cutting area. Therefore, the heat transfers from the chip to the cutting insert reduced with decreases in the friction time at the tool-chip interface. It is widely known that Inconel 718 super alloys are hard to machine owing to quick work hardening during the cutting process, resulting in heavy insert wear and a high tendency for BUE in conventional machining [30]. Acceptable improvements in notch wear and cutting edge breakage were observed during the external chip breaker-assisted turning of Inconel 718.

3.2. Characteristics of the machining force

The components of the machining force were measured in three directions using a standard tool holder with and without external chip breaker under the same experimental cutting conditions. The measured results for the surface roughness, cutting temperatures and cutting force are presented in Table 5. The resultant cutting forces measured during the experimental studies are effected by the machining speed, cutting feed, and depth of cut and are illustrated in Fig. 6 as multiple bar graphs

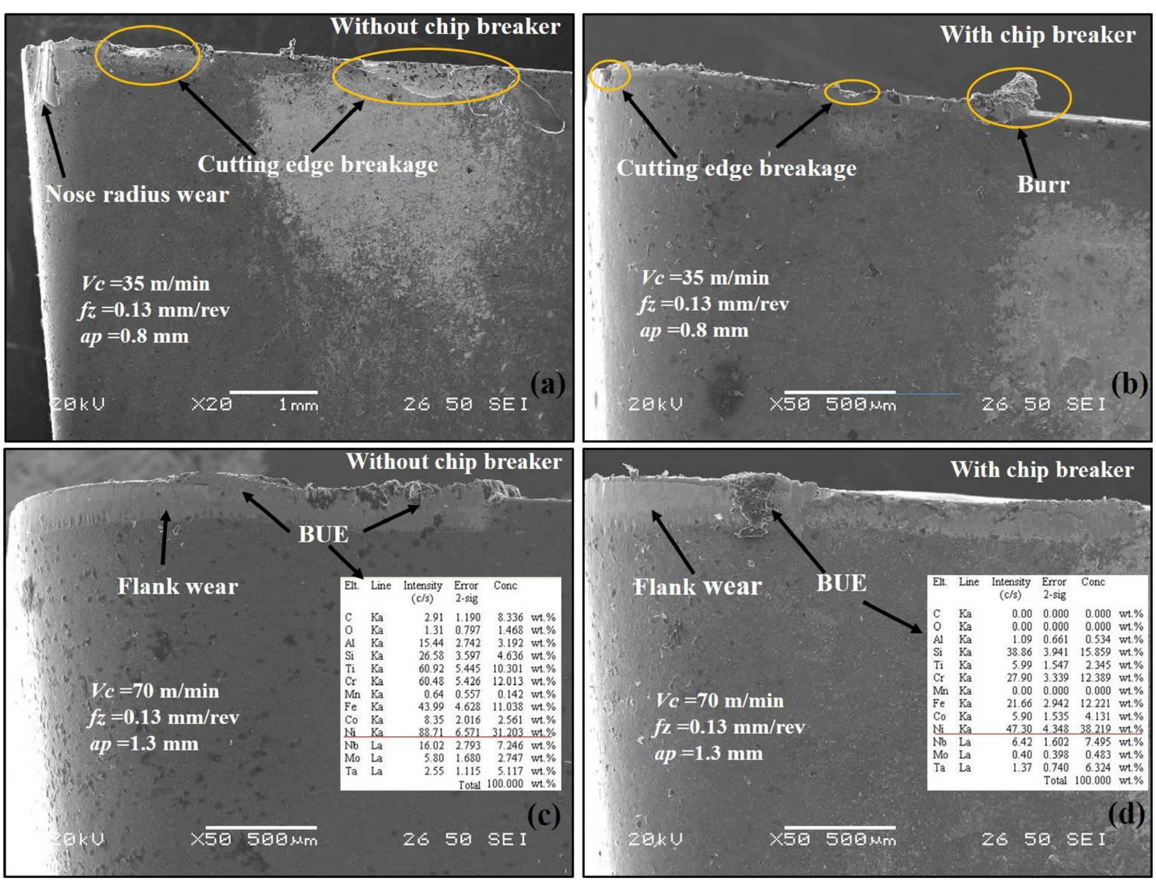

Fig. 5. SEM micrographs of the cutting tools used in the machining experiments.

Table 5
Experimental parameters and the recorded average roughness values.

Tests No	V_c (m/min)	fz (mm/rev)	a_p (mm)	Conventional turning Ft, (N)	Conventional turning C_T, (°C)	Conventional turning R_a, (μm)	Chip breaker-assisted turning Ft, (N)	Chip breaker-assisted turning C_T, (°C)	Chip breaker-assisted turning R_a, (μm)
1	25	0.10	0.8	374.4	405.40	0.987	357.1	345	1.842
2	35	0.13	0.8	391.4	402.30	1.128	414.5	362.3	1.684
3	50	0.17	0.8	492.8	392.50	1.576	490.7	376.3	1.546
4	70	0.22	0.8	589.1	386.00	2.094	561.6	384.5	1.302
5	25	0.13	1.0	542.2	413.60	1.353	526.5	364.9	2.402
6	35	0.10	1.0	410.9	418.90	1.079	447.3	367.6	2.187
7	50	0.22	1.0	755.1	400.90	2.049	705.5	397.9	1.979
8	70	0.17	1.0	612.4	398.60	1.873	550.6	388	1.428
9	25	0.17	1.3	909.4	433.80	1.522	868.6	392.6	2.750
10	35	0.22	1.3	947.4	427.30	2.240	972.1	405.2	2.651
11	50	0.10	1.3	580.9	433.40	1.976	555.7	388.5	1.935
12	70	0.13	1.3	649.9	420.82	2.340	601.5	400.8	1.784
13	25	0.22	1.7	1190.0	454.40	2.465	1160.0	414.7	3.403
14	35	0.17	1.7	1099.8	454.40	2.300	1067.4	409.9	3.018
15	50	0.13	1.7	861.3	460.00	2.484	805.3	412.6	2.821
16	70	0.10	1.7	701.7	455.20	2.776	626.3	413.8	2.378

to facilitate the ease of comparing the performance of the external chip breaker in the turning of Inconel 718. As expected, the resultant cutting forces increased at a higher depth of cut and feed rates and reduced with increases in cutting speeds (Fig. 7). The resultant cutting forces exhibited almost the same behaviors, and small differences were observed in both the tool holders used in the study. The maximum cutting forces were measured at a cutting speed of 25 m/min, a feed rate of 0.22 mm/rev, and a depth of cut of 1.7 mm in the turning process with respect to both the tool holders. The experimental results indicated that the resultant cutting force values were improved by 7% and 11% in the turning with the external chip breaker when compared with those with the standard tool holder at a cutting speed of 70 m/min in the same cutting conditions. This was related to chip formation and increased cutting temperatures at high cutting speeds. As shown in Fig. 5(a), tool edge breakage and notch wear on the cutting insert were observed at lower cutting speeds. Continuous chips were also trapped between the insert and workpiece in a few turning processes based on the cutting parameters. Hence, the cutting insert was reworked in conjunction with the trapped chips and the workpiece. Thus, the tool life diminished due to the high friction and temperatures that resulted in higher cutting forces. However, the external chip breaker that quickly removed the broken chips from the top of the cutting insert led to a decrease in the resultant cutting force. Conversely, the designed chip breaker exhibited a negative effect on the resultant cutting force in three turning tests at a cutting speed of 35 m/min when continuous chips were broken as a saw-tooth formation. This could be attributed to the cutting edge

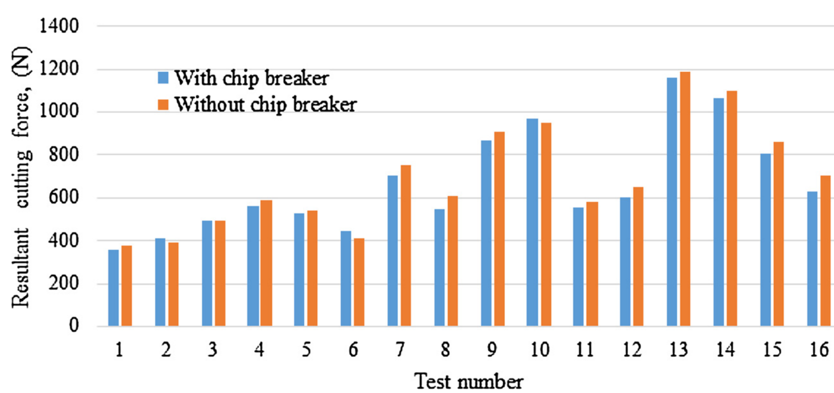

Fig. 6. Resultant cutting forces measured during the machining test with and without the chip breaker.

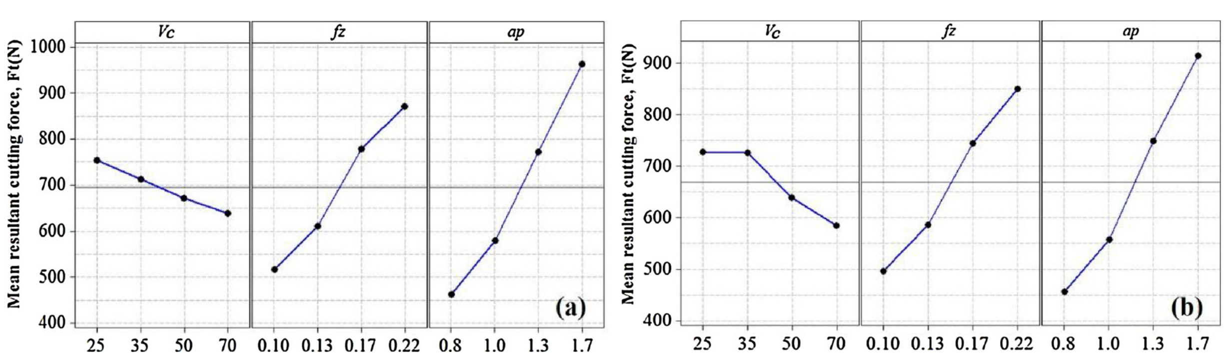

Fig. 7. The mean effect of the cutting parameters on the resultant cutting forces in the turning of Inconel 718 in (a) conventional machining and (b) chip breaker-assisted machining.

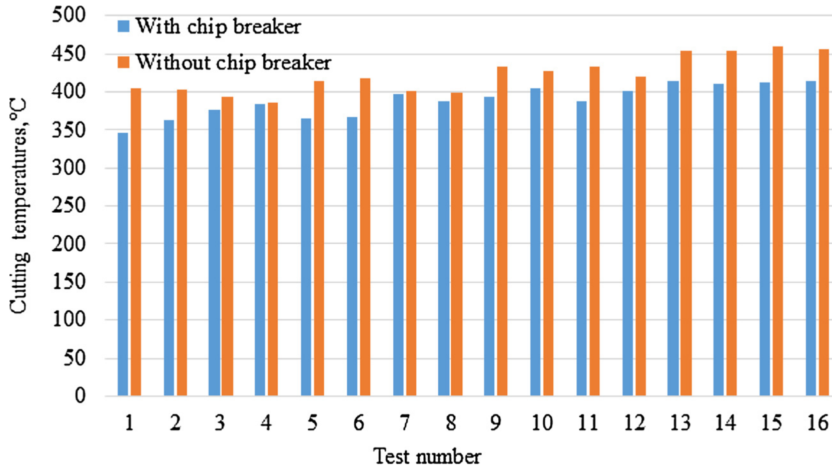

Fig. 8. Cutting temperatures measured during the machining experiments.

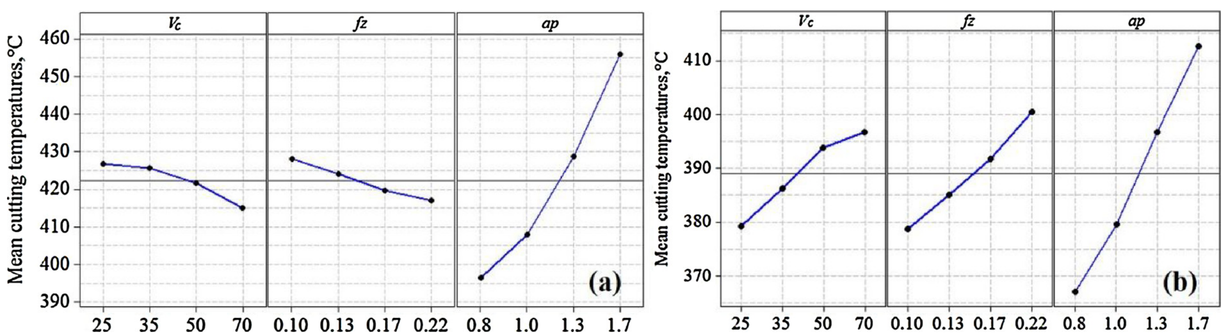

Fig. 9. The mean effect of the machining variables on the machining temperatures in the turning of Inconel 718 in (a) conventional turning and (b) chip breaker-assisted turning.

breakage, notch wear, and induced vibrations [4]. The experimental results indicated that more effective resultant cutting forces were measured at a low depth of cuts, low feed rates, and low cutting speeds in the cases of both the studied tool holders. The statistical interpretation of experimental data indicated that the external chip breaker did not produce a considerable chatter during the turning process.

3.3. Cutting temperature behaviors

The tool-chip interface temperatures were measured using a non-contact infrared pyrometer during the turning of Inconel 718. Additionally, the effect of the external chip breaker on the cutting temperatures was examined. The experimental temperature data was stored on the computer used in the cutting process. The calibration of the pyrometer was performed at constant machining conditions with a machining speed of 70 m/min, a cutting depth corresponding to 1.7 mm, and a feed rate corresponding to 0.22 mm/rev under different emissivity values ranging from 0.3 to 0.8 to obtain a precise cutting temperature measurement. The emissivity value in this study was specified as 0.60 for the temperature range from 350 °C to 500 °C based on pilot test results and previous studies [18,31,32].

Fig. 8 depicts the temperature variation during the experiments involving the turning process of Inconel 718 with conventional machining and chip breaker-assisted machining. The cutting temperatures slightly decreased in external chip-assisted machining. During the turning process, a significant amount of cutting energy was converted into heat because of the friction between the cutting tool and the workpiece material that resulted in the plastic deformation of the workpiece. Maximum temperatures exist on the cutting point between the tool and workpiece. Generally, approximately 70%–80% of the heat generated in the machining process was transported away by the flowing chip. The remaining heat in the cutting zone was dissipated between the cutting tool and workpiece material [32]. In the study, it was observed that the external chip breaker quickly removed the long chips from the cutting zone and reduced the contact length and time to the cutting tool. Therefore, the temperatures in the chip flowing zone decreased based on the cutting conditions and processing time. During the experiments, the machining parameters in the study also significantly affected the cutting temperatures in the cutting zone. The mean effect of the machining parameters on the cutting temperatures is shown in Fig. 9. Maximum cutting temperatures were observed with increases in the depths of cut in both machining conditions because the cutting temperatures are measured at the tool-chip interface. An increased depth of cut was associated with a wider chip surface and increased friction between the thicker chips and insert, and thereby increased energy dispersion occurred due to the friction of the chip on the tool face and higher shear strain. As a result, the machining temperatures increased at increased cutting depths in conventional machining and chip breaker-assisted machining.

The cutting speed and feed rates did not indicate a meaningful effect on the cutting temperatures in conventional machining. The heat generated in the cutting zone slightly decreased with increases in the cutting speed and feed rates. In contrast, the rate at which the cutting speed and feed rates influenced the cutting temperatures increased in the chip breaker- assisted turning of Inconel 718. The cutting temperatures increased with increases in the cutting speed and feed rates.

3.4. Surface roughness

Surface roughness values (R_a) were obtained from six measurements at six different regions along the cylindrical surface of the workpiece at the end of the every turning process. Maximum and minimum

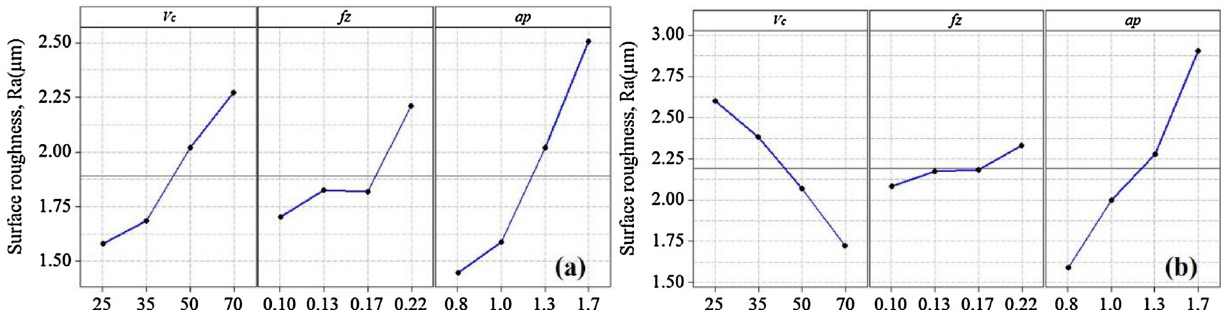

Fig. 10. The mean effect of the cutting parameters on the surface roughness in the turning of Inconel 718 in (a) conventional machining and (b) chip breaker-assisted machining.

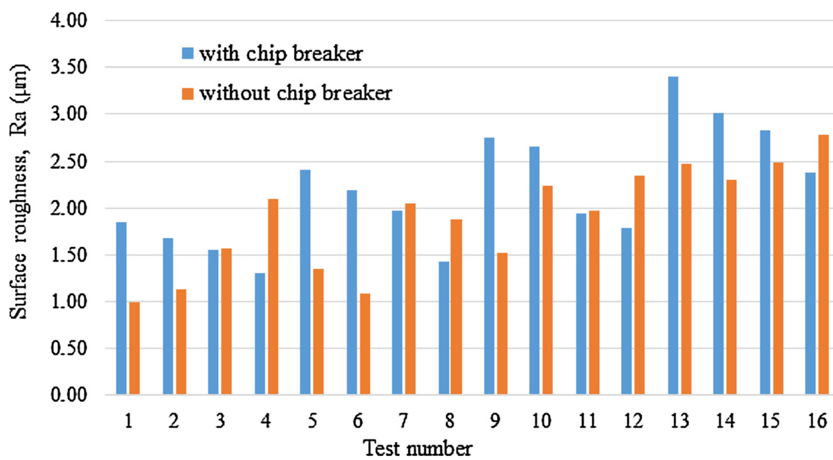

Fig. 11. Surface roughness measured during the machining experiments.

measurements were eliminated, and the average surface roughness values were computed. The measured values were analyzed by using Minitab software to compare the effect of external chip breaker-assisted machining and cutting parameters on the surface roughness. As shown in Fig. 10(b), the surface quality of the machined workpiece slightly improved by turning with the assistance of the external chip breaker, given the increases in the cutting speeds. The improvement in the surface finish using chip breaker- assisted machining was the result of improvement in tool life because of decreases in the notch wear, decreases in BUE formation, and reduced edge breakage owing to the effect of chip breaking and balanced cutting temperatures during the turning process (Figs. 5 and 8). Conversely, poor surface roughness values were measured at a cutting speed of 25 m/min. This is probably due to the increasing chip thickness and tendency of chip breakability at lower cutting speeds resulting in chatter in machining area. As can be seen from the Fig. 10(a), the surface roughness values were worsened with the increasing cutting speed in conventional machining of Inconel 718 because of the long chips leading to the wrapping and trapping around the tool and workpiece. The wrapping chips around the tool and work part were caused in a slight degradation in machined surface quality. The surface roughness is remarkably reduced with increasing feed rates and depth of cuts in both conventional and external chip breaker assisted machining, as expected. The optimal machining parameters for surface quality are achieved in external chip breaker assisted turning of Inconel 718, at cutting speed of 70 m/min, at depth of cut of 0.8 mm and feed rate of 0.10 mm/rev. However, the lowest surface roughness values were obtained at cutting speed of 25 m/min in conventional machining of Inconel 718. Fig. 11 depicts the comparison of with and without chip breaker assistance machining and better surface roughness results were observed in most of turning process without chip breaker assistance. This could be related to the thermal softening of material at higher cutting temperatures in the machining zone.

3.5. Analysis of variance

The experimental measurements were analyzed by performing an analysis of variance (ANOVA) to determine the effect of machining variables on the machining force, machining temperatures, and surface finish. Tables 6 and 7 indicate the ANOVA results obtained with respect to the machining force, machining temperature, and surface roughness in conventional machining and chip breaker-assisted machining, respectively, of Inconel 718. The ANOVA used parameters including

Table 6
Analysis of variance for the experimental results in conventional machining.

	df	*SS*	*F*	*P*	*PC*
Cutting forces, *Ft*					
V_c	1	28933	19.571	0.0008299	3%
f_z	1	297371	201.153	0	32%
a_p	1	578825	391.538	0	63%
Error	12	17740			2%
Total *SS*	15	922869			
Cutting temperatures, C_T					
V_c	1	325.42	55.61	0.0000077	4%
f_z	1	273.9	46.8	0.0000179	3%
a_p	1	8175.82	1397	0	92%
Error	12	70.23			1%
Total *SS*	15	8845.38			
Surface roughness, R_a					
V_c	1	1.17408	61.858	0.0000045	25%
f_z	1	0.49444	26.05	0.0002601	11%
a_p	1	2.71601	143.096	0.0000001	59%
Error	12	0.22776			5%
Total *SS*	15	4.6123			

Table 7
Analysis of variance for the experimental results in chip breaker-assisted machining.

	df	*SS*	*F*	*P*	*PC*
Cutting forces, Ft					
V_c	1	55464	43.494	0.0000256	6%
f_z	1	294426	230.887	0	34%
a_p	1	494384	387.694	0	58%
Error	12	15302		0	2%
Total *SS*	15	859576			
Cutting temperatures, C_T					
V_c	1	673.39	43.464	0.0000256	10%
f_z	1	1044.37	67.409	0.0000029	16%
a_p	1	4729.9	305.295	0	71%
Error	12	185.91			3%
Total *SS*	15	6633.58			
Surface roughness, R_a					
V_c	1	1.74717	156.933	0	31%
f_z	1	0.11791	10.591	0.006901	2%
a_p	1	3.59916	323.28	0	64%
Error	12	0.1336			2%
Total *SS*	15	5.59784			

degree of freedom (df), sum of squares (SS), F-test value (F), error variance (P), and percentage of contribution (PC) associated with each factor. The P value shows the statistical significance level of the test parameter, and the parameters are considered to be statistically significant if $P < 0.05$.

Table 6 shows the ANOVA results for conventional machining of Inconel 718 using the standard tool holder. The results indicated that the depth of cut was the most important parameter influencing the cutting force, cutting temperature, and surface roughness rates as it accounted for 63%, 92%, and 59% respectively. The feed rate has followed the depth of cut for the cutting force and surface roughness with a value of 32% and 11% respectively and negligible for the cutting temperature. The cutting speed influenced only the surface roughness with a contribution rate of 25%. The cutting forces and cutting temperatures were not influenced by the cutting speed in the conventional machining of Inconel 718. The cutting temperatures were not significantly affected by the feed rate and cutting speed. Table 7 presents the ANOVA results for the external chip breaker-assisted turning of Inconel 718 with the same cutting parameters as those of conventional machining. The contribution rate of the depth of cut with respect to the output results decreased when the cutting speed and feed rates increased when compared to those in conventional machining. The ANOVA results revealed that the depth of cut was the most significant machining parameter in the conventional machining of Inconel 718 influencing the cutting force, machining temperature, and surface roughness with percentage contributions of 58%, 71%, and 64%, respectively. The percent contribution of the feed rate to the cutting force, cutting temperature, and surface roughness corresponded to 34%, 16%, and 2%, respectively. Thus, increases in the feed rate did not significantly affect the surface roughness during turning with the external chip breaker. Similarly, based on the ANOVA results, the contribution rate of the cutting speed to the cutting force, cutting temperature, and surface roughness corresponded to 6%, 10%, and 31% respectively. The experimental results indicated that the cutting force, cutting temperature, and surface roughness values were significantly affected by the cutting depth in the turning of Inconel 718 with conventional machining as well as with the external chip breaker. The test results also showed that the cutting force and cutting temperatures slightly improved in the range of 3%–15% during machining with the external chip breaker when compared with that in conventional machining. The surface roughness values at cutting speeds of 70 m/min and 50 m/min improved and corresponded to 24% and 2%, respectively during turning with the external chip breaker. Conversely, the surface quality dramatically decreased at lower cutting speeds of 25 m/min and 35 m/min based on the feed rate and depth of cut.

Table 8
Response Table for S/N ratios for R_a and F (Lower values are consider as better).

Level	$A(V_c)$	$B(f_z)$	$C(a_p)$	Level	$A(V_c)$	$B(f_z)$	$C(a_p)$
Conventional machining				Chip breaker-assisted machining			
1	−53.65	**−51.69**	**−50.92**	1	−53.09	**−51.06**	**−50.53**
2	−53.28	−52.54	−52.22	2	−53.15	−52.04	−51.76
3	−53.13	−53.94	−54.07	3	−52.67	−53.51	−53.69
4	**−52.84**	−54.74	−55.69	4	**−52.21**	−54.50	−55.13
Delta	0.81	3.04	4.77	Delta	0.94	3.45	4.60
Rank	3	2	1	Rank	3	2	1

The experimental study was conducted based on the Taguchi design of experiments. The measurements were transformed into signal-to-noise (S/N) ratios to identify the quality of performance by minimizing the influence of uncontrollable factors. Lower values of the cutting force, cutting temperatures, and surface roughness are desirable for a reliable machining process, workpiece quality, and power consumption. Hence, there was a preference for smaller cutting characteristics in order to improve the quality characteristics. Higher values of S/N ratios were used to define the optimal machining parameters due to the minimization of the influence of the noise factor. The optimal cutting parameters for the conventional and chip breaker-assisted turning of Inconel 718 are presented in bold fonts in Table 8. Based on the S/N ratios in Table 8, the optimum machining parameters for cutting force, cutting temperatures, and surface roughness are determined at a cutting speed (A3) of 70 m/min, at a feed rate (B1) of 0.1 mm/rev, and at a depth of cut corresponding to 0.8 mm (C1) for both conventional and chip breaker-assisted turning.

The experimental measurements for cutting force (Ft), cutting temperature (C_T), and surface roughness (R_a) were analyzed by using Minitab 16 software. The experimental results were used to generate regression equations for Ft, C_T, and R_a in the conventional and chip breaker-assisted turning of Inconel 718. Regression analysis is a statistical method used to predict the relationship between the cutting parameters and indicates the correlation between the independent parameters and dependent parameters. Hence, if the R^2 values of the experimental results exceed 90%, then 95% of all the obtained results are within a reliable interval. Table 9 lists the regression equations for cutting force, cutting temperatures, and surface roughness. The R^2 values for all the experimental results exceeded 90%, and a good correlation was obtained between the cutting parameters and experimental outputs.

4. Conclusions

This study involved examining the machining properties and chip formation mechanism of Inconel 718. An external chip breaker system was developed to break continuous chips in the finish and semi-finish cutting conditions under a dry machining environment. The external chip breaker-assisted machining system was validated by analyzing the cutting forces, cutting temperatures, surface roughness, and tool wear behavior. The results were compared with those obtained in the conventional machining of Inconel 718 under the same cutting conditions.

Table 9
Regression models and R^2 values for the experimental results.

Regression models	R^2
Conventional turning of Inconel 718	
$Ft = -335.482 - 2.508 \times V_c + 3029.54 \times fz + 560.873 \times ap$	98.98%
$C_T = 368.575 - 0.265978 \times V_c - 91.9444 \times fz + 1.21495 \times ap$	99.21%
$R_a = -0.892238 + 0.0159761 \times V_c + 3.90648 \times fz + 1.21495 \times ap$	95.06%
External chip breaker-assisted turning of Inconel 718	
$Ft = -263.603 - 3.47237 \times V_c + 3014.5 \times fz + 518.35 \times ap$	98.22%
$C_T = 283.151 + 0.382609 \times V_c + 179.537 \times fz + 50.7011 \times ap$	97.20%
$R_a = 1.09724 - 0.019489 \times V_c + 1.90765 \times fz + 1.39859 \times ap$	97.61%

The chip surface morphologies and cutting tool wear behavior were evaluated based on the cutting parameters. The results indicated that all the machining parameters exerted a significant influence on the tool behavior, chip formation, cutting forces, temperatures, and surface roughness. The main findings are summarized as follows:

- Despite the chip breaker geometry of the insert, long snarled and tubular chips were formed in conventional machining under all cutting conditions. Conversely, long chips were efficiently broken by the impact and force acting on the chip surface in the external chip breaker-assisted machining.
- The chip formation was mostly affected by the chip breaker system and cutting parameters. A saw-tooth chip formation with a rough surface was observed at a low cutting speed, high feed rate, and high depth of cut. The chip formation turned from a rough saw-tooth type to a smooth, wavy saw-tooth type having a better surface with increases in the cutting speed.
- Notch wear, cutting edge breakage, and BUE formation were observed in conventional machining. The tool life significantly improved with increasing cutting speed, lower feed rate, and lower depths of cut in chip breaker-assisted machining. Tool wear reduced with the use of the chip breaker system.
- The optimal machining parametric combination in terms of the cutting force, cutting temperatures, and surface roughness was observed at $A_3B_1C_1$ in the turning of Inconel 718 with conventional machining as well as with chip breaker-assisted machining given a machining speed of 70 m/min, a feed rate of 0.8 mm/rev, and a depth of cut equal to 0.8 mm.
- The ANOVA results indicated that the depth of cut was the most significant machining parameter in conventional machining of Inconel 718 influencing the cutting force, machining temperature, and surface roughness with percentage contributions of 63%, 92%, and 59%, respectively. Conversely, in chip breaker-assisted machining, the percentage contribution rate of the depth of cut to the cutting force, machining temperature, and surface roughness corresponded to 58%, 71%, and 64%, respectively.
- The cutting force and cutting temperatures slightly reduced in the range between 3% and 15% during turning with the external chip breaker when compared with those in conventional turning using the standard tool holder.
- The surface quality of Inconel 718 improved with increases in the cutting speed and decreases in the feed rate and depth of cut that corresponded to 24% and 2%, respectively. In contrast, the surface quality significantly decreased at low cutting speeds of 25 m/min and 35 m/min based on the feed rate and the depth of cut in external chip breaker turning.
- Future studies will involve performing detailed experimental studies on tool life, surface roughness, and cutting forces using a coolant and minimum quantity lubrication (MQL) and examining their effects on the chip breaker-assisted machining of Inconel 718.

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 splitted up 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.

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