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ORIGINAL PAPER

Sustainability Assessment and Machinability Investigation of Austenitic Stainless Steel in Finish Turning with Advanced Ultra-Hard SiAlON Ceramic Tool under Different Cutting Environments

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Abstract

This paper presents the evaluation of the performances of the various cooling-lubrication techniques (dry, compressed-air cooled, flooded and minimum quantity lubrication) applied in turning of austenitic stainless steel Nitronic 60 with new-generation SiAlON ceramic tool in terms of cutting force, tool wear, cutting temperature, and surface roughness. Machining experiments were performed in a heavy-duty lathe machine tool under cutting conditions associated with varying cutting speeds (51, 67, 87, and 111 m/min), feed rates (0.12, 0.16, 0.20, and 0.24 mm/rev) and a constant depth of cut (0.4 mm). Consequently, analysis on machined surface roughness and tool as well as crater wear mechanism was made by using scanning electron microscope with an embedded energy dispersive X-ray analyzer for comprehensive understanding of the process. Finally, the Pugh matrix environmental approach has been proposed for sustainability assessment in finish turning process under various cooling-lubrication strategies. Among the four pre-cited cutting environments, the cutting fluids were applied to the cutting zone in sprayed-jet form by MQL technique significantly outperformed due to the lower environmental and health impacts. Also, it was observed that both main cutting force and surface roughness reduced with the increase of cutting speed whereas, with feed, both force, roughness and temperature increased but tool wear reduced. The results indicate that machining with MQL technique provided environmental friendliness, cleaner production and helped to enhance sustainability.

Keywords Machinability · Nitronic 60 · SiAlON ceramic · Cooling-lubrication technique · Sustainability assessment

1 Introduction

Day-by-day, the nickel-based alloy is being popularly used because of its excellent mechanical and chemical properties. Properties such as formability, weldability, toughness, high-temperature as well as corrosion resistance, sustainability and ease in production have brought very much importance application in different industries to attain high performances. Nickel-based alloys are extensively used in various industries such as architecture building and construction, oil and gas power industries, transport, process engineering, food processing equipment, medical applications, nuclear power systems and in various consumer products.

Despite the presence of many advanced machining techniques, machining is still considered as one of the extensively used processes as it becomes easy for the manufacturer to get desired shape, size, surface finish and to impart all the functional features. However, some of the major challenges involved in the machining are the generation of stress and temperature which majorly affects the tool life and machining forces which further affects the surface integrity of the machined surface. If the considered cutting parameters do not suit the tool and workpiece combination it can lead to failure of the cutting tool or improper machining of the workpiece exceeding the acceptable limits. Therefore, effective cooling and lubrication technique is quite essential in order to overcome the

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above-mentioned issues which will be beneficial form economical, ecological, and technological point-of-views. The application of cutting fluids by various cooling-lubricating methods considerably reduce friction, provide heat control, prevent corrosion, improve chip removal and increase cutting efficiency [1]. Cooling function is achieved by removing the heat from the cutting zone by the continuous cutting fluid flow. Cutting fluids provide the lubrication function by creating an oil film layer on the cutting zone depending on the adhesion and cohesion forces of the cutting fluid. Many researchers have used different cooling-lubrication methods [2–11] in turning operation to improve the cutting performance [12–17] and machinability [18–24] of different difficult-to-cut and hard-to-cut materials (Inconel-718, Inconel-800, Inconel-825, Ti6Al4V, Haynes-25, EN-24, EN-31, AISI 202, 316, 420, 1015, 1045, 1060, 4140, 4340, 52,100, D2, 42CrMo4, 17CrNiMo6). Table 1 shows the extensive studies carried out to analyze the performance of machining under different cooling-lubrication techniques and their effects on cutting force, surface roughness, cutting temperature, tool wear, chip morphology, and surface integrity on various workpiece materials and machining conditions with different cutting tool materials. Similarly, several publisher works have used methods include experimental and analytical approach in turning operation for modeling in order to predict as well as control the cutting temperature and force, as summarized in Table 2. Chinchanikar et al. [2] used carbide tools coated with HiPIMS coating techniques. They used three kind of coatings such as nano composite AlTiN, nano composite multilayer TiAlN/TiSiN and nano crystalline AlTiCrN in hard turning of AISI 4340 low alloy steel under dry and MQL condition. In their research they investigated the effect of these nano-coatings on wear mechanism and wear rate under dry and MQL condition. From their experimental data it is observed that, minimum quantity lubricant condition significantly improved tool life than dry turning. As MQL condition can provide both cooling and lubrication effects and also help to form a powerful protective layer around the nanocomposite coated tool. Also, it was observed that machining under dry environment lowered the tool life by almost 20–25% when it used in MQL condition. Pandey et al. [17] compared the machining performance (cutting temperature, surface roughness and chip thickness ratio) of near-dry lubrication (NDL) machining condition with dry and flooded turning on hardened AISI 1060 carbon steel. From their study they observed that NDL significantly reduced cutting temperature, improved surface quality and also increased the value of chip thickness ratio. In another study where AISI -4340 material was used, Saini et al. [3] investigated the effect of cutting parameters (i.e. feed rate, approach angle, cutting speed and depth of cut) on cutting forces and tool-tip temperature using two different coated cutting tools under dry and MQL condition. They reported that PVD (TiCN/TiN) coated tool gave better results than CVD (TiCN/Al_2O_3) coated tools in terms of cutting forces and tool- tip temperature under MQL condition. The reason is that PVD coated inserts having TiCN/TiN layer helps in providing dry lubrication for better chip control, and it reduces the adherence of chips to the cutting edge (which is very helpful for protecting the insert from built-up-edge) and also provides good heat isolation by forming a protective oxide layer on the cutting edge. Gupta et al. [10] investigated the effect of wet, dry and MQL techniques on cutting force, surface roughness, potential of tool wear and chip contact length in turning Inconel-800 super alloy. They stated that machining with MQL resulted in better values of considered output responses. They also applied PSO and TLBO algorithm to perform a parametric optimization for their experiment. Ramanuj Kumar et al. [24] examined during machining process of hardened AISI D_2 steel under spray impingement cooling using coated carbide insert. They stated that machining with spray impingement cooling resulted in enhancement of surface quality and tool life, reduction of cutting temperature and tool wear. In addition, it also enhanced the chip breakability due to the effective cooling.

As par with existing literature till due, systematic analysis on machinability under various cutting environments (dry, flooded, compressed air cooled, and MQL) is quite inadequate. The previous works related to machining especially, turning with various cutting tool materials such as: carbide tool [5–7, 9, 11, 13, 15], coated carbide tool [2–4, 8, 14, 17, 18], ceramic tool [23], CBN tool [10, 12, 20], and cermet tool [21, 22]. However, turning with the use of new-generation SiAlON ceramic tool is a still relatively new research area, and only a few researchers [30] have studied. In particular, very limited research works have been reported concerning finish turning of Nitronic 60 stainless steel with newly developed SiAlON ceramic tool, which plays a very important role for improvement of machinability as well as enhancement in machining performance. Literature review highlights that the realistic approach to justify the use of cutting fluid in MQL technique as an effective cooling/lubrication strategy in machining of difficult-to-cut materials is less outlined, which finds the scope for researchers. From the published works in the scientific database, it has been revealed that, the investigation deals with sustainability assessment in turning typically, in today's manufacturing society that ensures green development towards safer environment is still unexplored, which finds an ideal worthy of investigation in the present paper. Thus, this work does not only focus on the machining performance, but also considers the sustainability aspects. In view of such contribution, the current study aims; (i) to analyze the cutting performance of new-generation SiAlON ceramic tool, (ii) to investigate the machinability of Nitronic 60 concerning tool wear, cutting force, surface roughness, cutting temperature under various cooling-lubrication conditions, (iii) to explore a comparative investigation towards machinability

Table 1 Cooling-lubrication techniques used in various study

References	Materials studied	Cutting tool material	Cooling-lubrication techniques	Machining parameters	Machining responses evaluated	Silent findings
(a) Cutting performance						
[2]	AISI 4340 steel	Coated carbide tools	Dry and MQL	Cutting speed, feed, depth of cut	Tool wear progression and failure mode, tool wear mechanism	Improvement in tool life under MQL condition due to lower cutting temperature
[3]	AISI 4340 steel	Coated carbide inserts	Dry and MQL	Approach angle, cutting speed, feed rate	Cutting forces component and the temperature variations on the tool-tip	• The MQL reduced all the components of cutting forces including cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges. • During cutting PVD-TiAlN layer provides good heat isolation by forming a protective oxide layer on the cutting edge which prevents the insert from fast wear.
[4]	AISI 420 steel	Coated carbide tool	MQL	Cutting speed, feed, depth of cut, flow rate, air pressure	Tool life, surface roughness, and cutting forces	A combination of low cutting speed and feed was the optimum cutting parameters to achieve long tool life, low surface roughness, and low cutting forces.
[5]	Haynes 25	Carbide tool	MQL	Cutting speed, feed, depth of cut, flow rate, types cutting fluids	Flank wear, notch wear and surface roughness	Performance indicators are significantly improved using GRG optimization technique.
[6]	17CrNiMo6, 42CrMo4 steel	Carbide tool	Dry and HPC	Cutting speed, feed rate	Chip–tool interface temperature.	HPC-assisted machining reduces chip–tool interface temperature

Table 1 (continued)

References	Materials studied	Cutting tool material	Cooling-lubrication techniques	Machining parameters	Machining responses evaluated	Silent findings
						significantly as well as prolongs tool life.
[7]	Inconel 825	Coated carbide	Dry and MQL	Cutting speed, feed, depth of cut	Surface roughness, tool flank wear and cutting power	Significant improvement in MQL machining in terms of reduction in tool wear, power consumption and surface roughness.
[8]	AISI 1060 steel	Coated carbide tool	Dry, wet, MQL, SL + CA	Cutting speed, feed, depth of cut	Cutting temperature, surface roughness, chip characteristics and tool wear	• MQL system can ameliorate the heat transfer problem, and divulge quite promising results. • MQL system provides environment friendliness, cleaner production and helps to improve the desirable machinability characteristics.
[9]	AISI 316 steel	Carbide inserts	Dry and SIC	Depth of cut, feed rate, cutting speed, water pressure, air pressure	Cutting tool temperature, chip temperature, surface roughness and tool flank	Machining under spray impingement cooling environment was most effective in turning AISI 316 steel in comparison with dry machining since reduction in chip temperatures were found out to be greater than 300%.
[10]	Inconel 800 alloy	CBN insert	Dry, wet and MQL	Cutting speed, feed, side cutting edge angle	Cutting force, tool wear, surface roughness, tool–chip contact length	MQL was found to be a better cooling technique when compared to the dry and the flood cooling. As it reduced cutting forces, tool wear, surface roughness, and tool–chip contact length.

Table 1 (continued)

References	Materials studied	Cutting tool material	Cooling-lubrication techniques	Machining parameters	Machining responses evaluated	Silent findings
[11]	AISI 1045 steel	Carbide insert	Dry, flooded, and NFMQL	Cutting speed, feed, depth of cut	Surface roughness, power consumption	•MQL-nanofluid offered promising results compared to dry and flood approaches. •The nano-mist serves as rollers in the cutting zone, which affects and improves the friction behavior, and hence a better machining performance was observed when machining under MQL-nanofluid.
[12]	AISI 4340 steel	CBN insert	Dry, wet and MQL	Cutting speed, feed, depth of cut	Surface roughness, cutting forces	Turning under MQL conditions has shown superior results over wet and dry turning in terms of minimum chip thickness, low cutting force and machined surface roughness.
[13]	AISI 1015 steel	Carbide insert	Dry and SIC	Spindle speed, feed rate, depth of cut, air pressure	Cutting temperature, surface roughness and MRR	Reduction in cutting temperature and BUE formation resulted in better surface finish in spray impingement cooling environment.
[14]	AISI 202 steel	Coated carbide	MQL	Cutting speed, feed, flow rate	Flank wear and surface roughness	Turning under MQL conditions has shown superior results over wet and dry turning in terms of low tool wear and machined surface roughness.
[15]	EN-31 steel	Carbide tool	Dry, wet and solid lubricants mixed with oil	Cutting speed, feed and depth of cut	Cutting temperature, surface roughness, power consumption and tool wear	Solid lubricant assisted machining performs better and improves surface finish, reduces temperature,

Table 1 (continued)

References	Materials studied	Cutting tool material	Cooling-lubrication techniques	Machining parameters	Machining responses evaluated	Silent findings
						tool wear and power consumption, due to excellent lubrication properties.
[17]	AISI 1060 steel	Coated carbide tools	Dry, wet and NDL	Cutting speed, feed and depth of cut	Chip tool interface temperature, surface roughness, and chip thickness ratio	•Chip thickness ratio is largely influenced by cutting condition, which is respectively followed by cutting speed, feed rate, and depth of cut. •Chip thickness ratio appeared with higher values for NDM, because NDM provided better lubrication.
(b) Machinability investigation						
[18]	AISI 4140 steel	Coated ceramic tool	Dry	Cutting speed, feed and depth of cut	Machined surface characterization, tool wear mechanism and chip morphology	•Feed is the principal cutting parameter influencing surface roughness, followed by cutting speed. •Flank wear is affected by the cutting speed and interaction of feed-depth of cut. •No chipping and catastrophic failure of cutting edge are noticed for TiN coated ceramic insert at low feed (0.05 mm/rev) and 0.2 mm depth of cut as TiN coating appreciably enhances the fracture resistance as well as wear resistance of Al_2O_3 + TiCN mixed ceramic inserts
[19]	AISI D2 steel		Dry			

Table 1 (continued)

References	Materials studied	Cutting tool material	Cooling-lubrication techniques	Machining parameters	Machining responses evaluated	Silent findings
		Coated and uncoated carbide inserts		Cutting speed, feed and depth of cut	Surface roughness, flank wear, chip-tool interface, chip morphology, temperature	•The abrasive wear resistance of Al_2O_3 coated carbide tool was four times more than that of the uncoated carbide tool. •The depth of cut and cutting speed were determined as the most dominant parameters influencing the CRC. •The machined surface quality by the coated carbide insert was better than that by the uncoated carbide insert at each cutting combination
[20]	Inconel 800	CBN tool	Dry and NDM	Cutting speed and feed rate	Cutting force, surface roughness, tool wear rate, and chip morphology	•Abrasion rate of cutting insert is 14 × 10–5 g/min which confirms of highly resistant against abrasion of cutting insert.
[21]	EN-24 steel	Coated cermet	Mist cooled and dry	Cutting speed, feed and depth of cut	Cutting force, flank wear, chip morphology, crater wear, surface roughness and chip microhardness	•Cutting speed and feed influenced inserts crater wear most significantly compared to depth of cut. •Speed and depth of cut were observed to be statistically important for cutting force, but feed was not important.
[22]	AISI 4340 steel	Cermet insert	Compressed air, MQL, NFMQL	Cutting speed, feed and depth of cut	Cutting force, tool wear, surface roughness, microhardness, morphology of	Superior surface finish and better surface quality, reduction in principal cutting

Table 1 (continued)

References	Materials studied	Cutting tool material	Cooling-lubrication techniques	Machining parameters	Machining responses evaluated	Silent findings
					machined surface & chip, apparent coefficient of friction	force and flank wear were observed with nanofluid machining compared to compressed air and water-soluble coolant machining.
[23]	AISI 4340 steel	Coated ceramic insert	Dry	Cutting speed, feed and depth of cut	Surface roughness, flank wear, chip morphology	•Surface roughness is principally affected by feed but the opposite is seen with cutting speed. •Flank wear (VB) firstly decreases marginally with the increase of feed (upto 0.1 mm/rev) and increases significantly with increase in cutting speed and depth of cut.
[24]	AISI D2 steel	Coated carbide tool	SIC	Cutting speed, feed and depth of cut	Tool wear, cutting temperature, CRC, surface roughness	•Spray cooling utilizes a spray of small droplets impinging on a heated surface to increase the effectiveness of heat transfer as a cooling mechanism with phase change. •Wear at flank surface and roughness of machined workpiece are much below of 0.2 mm and 1.6 μm respectively with cutting temperatures lies between 120 °C to 217 °C which shows advantage of compressed air-water spray cooling.

Table 2 Summary of experimental and modelling methods in the investigation of the machining process

Techniques	Experimental Techniques	Analytical Methods
	Dynamometer [21, 25], Tool-work thermocouple [8] IR camera [9] Thermal imaging camera [19]	•J-C constructive model [25–27, 29], •Chip formation model [26], •Mechanics model [27, 29], •Extended chip formation model [25], •Modified chip formation model, Komanduri-Huang model, and Ning-Liang model [28]
Major advantage	•Enough accuracy for in-situ/post-processing measurement.	•High computational efficiency •Allows real-time prediction
Major disadvantage	•High experimental complexity •Possibility of human, machining and measurement error •Time consuming process	•Complex input requirement •high mathematical complexity •extensive material property test

improvement using under dry, compressed air cooled, wet and MQL conditions, (iv) to study the effect of cutting environments, cutting speed and axial feed on various machining characteristics, and (v) to address the comprehensive sustainability assessment comparing the performance of different cooling techniques during machining. Novelty aspects, the present work (i) lies on enhancing the heat extraction capacity using different cooling-lubrication strategies in order to improve material machinability, (ii) proposes the alternative of costlier CBN tool by utilizing new-generation SiAlON ceramic tool in turning process of difficult-to-cut materials considering techno-economical and ecological aspect, which are helpful and efficient from industrial point of view, and (iii) contributes as a technological guideline for practical industrial application of finish turning operation in shaft and bearing makers to select the optimum machining conditions. All of these points bring the worthy investigations, contribute to the uniqueness of the current study, and make advancements towards sustainable manufacturing.

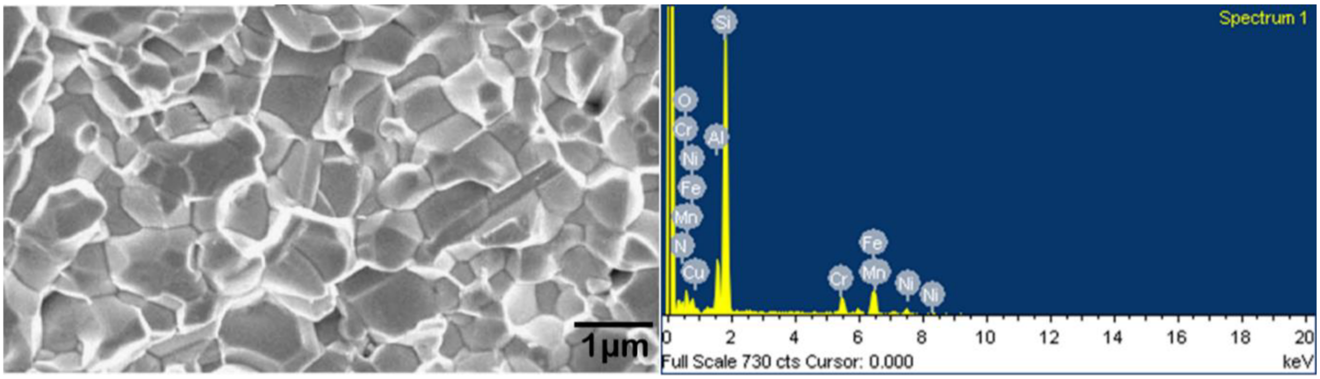
2 Experimental Setup and Procedure

In the present experimental investigation, anti-galling, and wear resistance austenitic stainless-steel grade, especially Nitronic 60 of cylindrical bar having dimension ϕ50 × 500 mm (diameter and length respectively) is considered as workpiece material due to its wide usage field in marine and manufacturing industry. Table 3 shows the chemical composition as well as properties of Nitronic 60 stainless steel and confirms the elemental composition of workpiece material after performing the test through stationary metal analyzer (SpectroMax). In the experiment, new-generation SiAlON ceramic tool (grade: KYS30, make: Kennametal) in the form of SNMG 120412 is preferred as a cutting tool which is clamped rigidly on an ISO designated tool holder with specification of PSBNR2020K12. The elemental constituents and structure of the tool substrate are identified (refer, Fig. 1) in a scanning electron microscope with an embedded energy dispersive X-ray (EDS) analyzer. The microstructure of SiAlON ceramic comprised uniform equiaxed grain morphology with average grain size of approximately 0.5–1.0 m, reflecting the inherently higher hardness of the fine-grained sialons imparts greater resistance to material removal. Prior to machining, undesirable effects and irregularities in the form of oxide layers are removed from the exterior surface of the specimen followed by mounting at tailstock. In order to create the same conditions in all experiments, new (unused) cutting tools were used in each experiment.

In this study tool wear (flank wear and crater wear), surface roughness, cutting force, cutting temperature are considered as technological response characteristics for machinability investigation and sustainability assessment. Four different cooling – lubrication strategies (dry, compressed air, flooded, MQL), four levels of cutting speed (51 m/min, 67 m/min, 87 m/min, 111 m/min) and four different levels of feed (0.12 mm/rev, 0.16 mm/rev, 0.20 mm/rev, 0.24 mm/rev) are defined as input parameters. In each machining trail, depth of cut was kept

Table 3 Chemical composition and properties of Nitronic 60

Elements	C	Cr	Mn	Si	Ni	P	S	N	Fe
Weight percentage	0.04	17.3	7.4	3.8	8.6	0.007	0.011	0.158	Remainder
Properties	Density	Poisons ratio	Tensile strength		Modulus of elasticity		Thermal conductivity		Vickers hardness
	7622 kg/mm^3	0.298	395 MPa		200 GPa		51.9 W/mK		115 HV



(a) (b)

Fig. 1 **a** SEM micrograph and **b** EDX analysis of SiAlON ceramic tool

content at 0.4 mm and machining time for 120 s. The cutting condition are selected based on the recommendation information of the tool manufacturer catalogue [31] as well as available information used cutting inserts in the open literature supported by the previous work [30, 32]. The parameter ranges were extended in order to investigate the behaviour of the tool/ material couple (SiAlON/Nitronic 60) in different machining conditions. Under each cooling–lubrication condition, machining is performed with seven experimental trails, i.e. a total twenty-eight numbers of trials are carried out by considering under pre-cited cutting environments. The details of experimental design layout considering of different levels of cutting speed and feed along with cooling condition for machining, is stated in Table 4. All the experimental runs are performed in various working environments are repeated three times and their mean values are taken to diminish the experimental errors.

For performing the straight cylindrical turning, a heavy duty-high accuracy machine tool lathe (make: HMT ltd.) with maximum power capacity of 11 kW, and the maximum speed upto 2040 rpm is used. The lubricating cutting fluid used in the conventional flooded cooling as well as MQL was made of a volume of ethylene-glycol based ecofriendly radiator coolant (type Wurth coolant concentrate, manufactured by Anchemco Ananda, India) diluted and homogenized in ten equivalent volumes of distilled water. The lubricant was directed to the cutting zone through nozzle. Regarding MQL, the cutting fluid was operated using a spray pump (make: Master Lube Engineers) of 3.5 kW, connected to a 1-l tank capacity at a flow rate of 50 ml/h and at a pressure of 4 bar. Readily available compressed air was used for cooling without any treatment at a pressure of 5 bar. During turning of Nitronic 60 steel, a piezoelectric dynamometer (make: Kistler, Model: 9257B) is used to measure the principal cutting force (Fc) which act in tangential direction. Measurement of surface finish of the machined part concerning arithmetical mean roughness value (R_a) is measured with the help of roughness tester (make: Mitutoyo, model: Surftest SJ-210). After every successive experimental trial, the tool wears which includes both flank and rake surfaces of the cutting insert is measured by using high resolution imaging digital microscope (make: Carl Zeiss, model: Axiotech 100HD-3D). For measuring the temperature at work-tool interface (i.e. cutting temperature) a dual laser infrared thermometer (make: Extech, model: 42570) is employed

Table 4 Experimental plan layout

Test no.	Cutting speed, v (m/min)	Feed rate, f (mm/rev)	Depth of cut, d (mm)	Cutting environments
1	51	0.24	0.4	•Dry •Compressed air •Flooded •MQL
2	51	0.20	0.4	
3	51	0.16	0.4	
4	51	0.12	0.4	
5	67	0.12	0.4	
6	87	0.12	0.4	
7	111	0.12	0.4	

which displayed the varying temperature throughout the run but maximum value of recorded temperature is considered. In the visual evaluation phase, morphological study and elemental analysis of tool wear as well as machined surface are performed for comprehensive understanding of cutting phenomena by employing scanning electro-microscope (make: JEOL, model: JSM-6084LV). The details of experimental methodology followed and equipments used are schematically layout in Fig. 2 to carry out the present work.

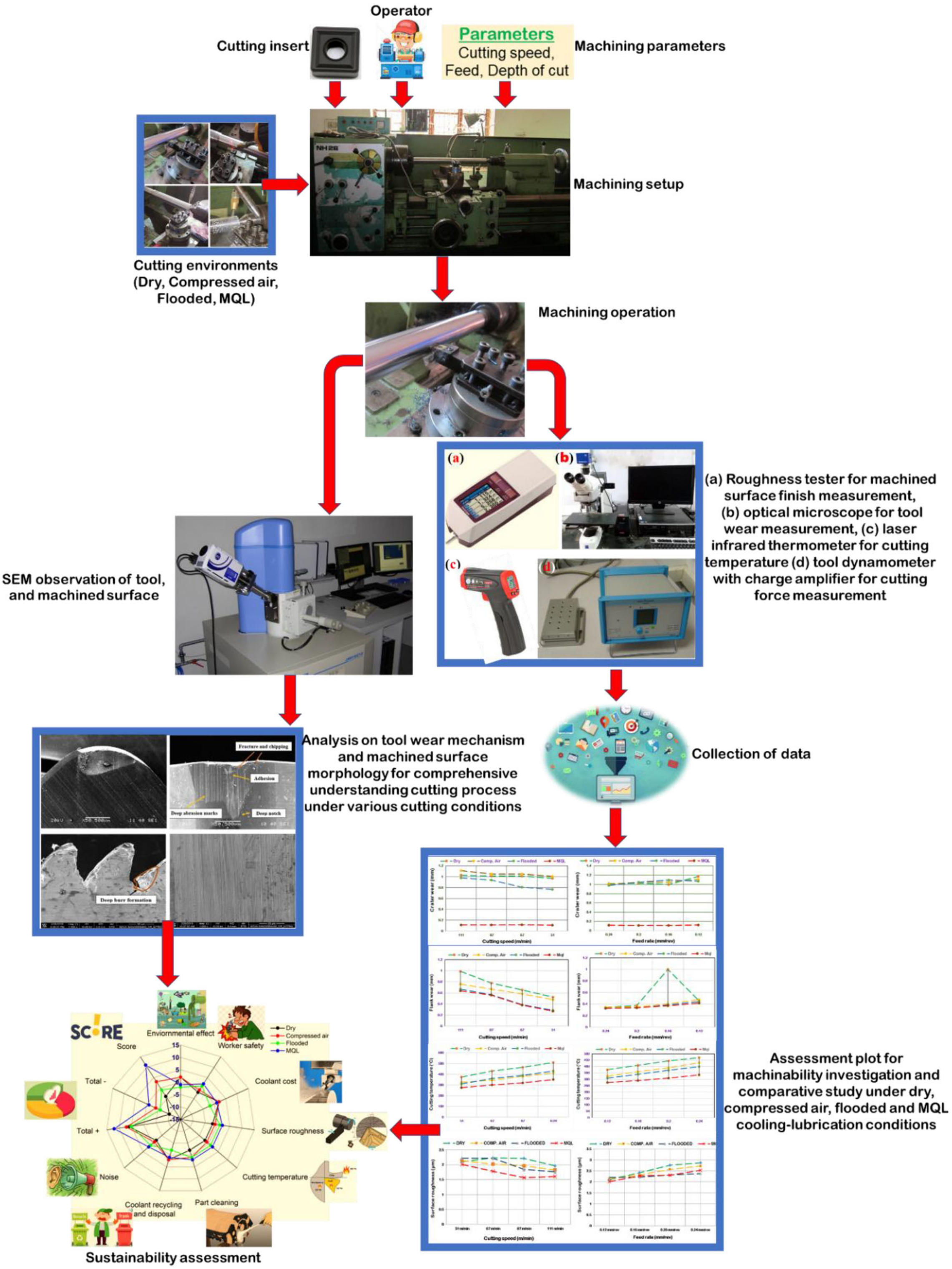


Fig. 2 Layout of experimental setup including methodology proposed

3 Results and Discussion

3.1 Crater Wear Analysis

Crater wear which occur in rake face of the tool is mainly based on the contact mechanism at the interface between chip and tool. At machining zone, due to elevated temperature, the material from chip gets stuck on tool wear void and causes adhesion type of wear. Whereas the chemical affinity between tool and workpiece material results in diffusion type of wear. Figure 3 shows the SEM micrograph of SiAlON ceramic tool used in machining of Nitronic 60 under dry cutting condition while cutting speed was 51 m/min and axial feed vary from 0.16 mm/rev to 0.24 mm/rev. When feed was 0.24 mm/rev, the damage on rake face of the cutting insert was found to be minimum as the time of contact between workpiece and tool was less, but when axial feed reduced to 0.20 mm/rev and 0.16 mm/rev, the time of contact between tool and workpiece increased and thus it promotes more damage on the cutting tool in form of crater wear. Whereas it was noticed from Fig. 4 that at high cutting speed and low feed under dry condition (i.e.111 m/min and 0.12 mm/rev), the chip particles adhered to the rake face of the tool. As high heat was generated because there was less time to transfer heat and also the heat generated was even higher in dry cutting condition. But when the cutting speed decreased to 87 m/min, the temperature generated was less and thus there was very less adhesion and the wear also decreased. It was observed that cutting has dominating effect on crater wear as compared to feed when depth of cut is kept constant. It was also observed that adhesion and chipping were predominant mode of failure of SiAlON ceramic tool under dry cutting condition.

The optical micrograph of crater wear on SiAlON ceramic tool under compressed air condition at four various cutting speeds (i.e. 111, 87, 67 and 51 m/min) and constant low axial feed rate (i.e. 0.12 mm/rev) are shown in the Fig. 5. At higher cutting speed of 111 m/min and low feed rate of 0.12 mm/rev cutting condition and due to the less thermal conductivity of compressed air the temperature produced at tool and workpiece interface is high which results thermal stresses and causes cracking followed by chipping of the tool. Additionally, because of high-temperature chip adhesion also occurs on the tool. Consequently, when speed gradually decreases from 87 m/min, 67 m/min and 51 m/min keeping the feed rate constant at 0.12 mm/rev, the tool and workpiece interface temperature decreases and also the tool wear. As the heat produced is less, no cracking occurs on the tool. Also due to less temperature generation the heat is not sufficient for adhering of the chip on the rake surface of the tool. But at the cutting speed of 67 m/min, built-up-edge was observed. But, when feed changes from 0.16 mm/rev, 0.20 mm/rev and then 0.24 mm/rev keeping the cutting speed constant at 51 m/min, the wear on the rake face of insert decreases due to the decrease in wear as result of increase in contact time

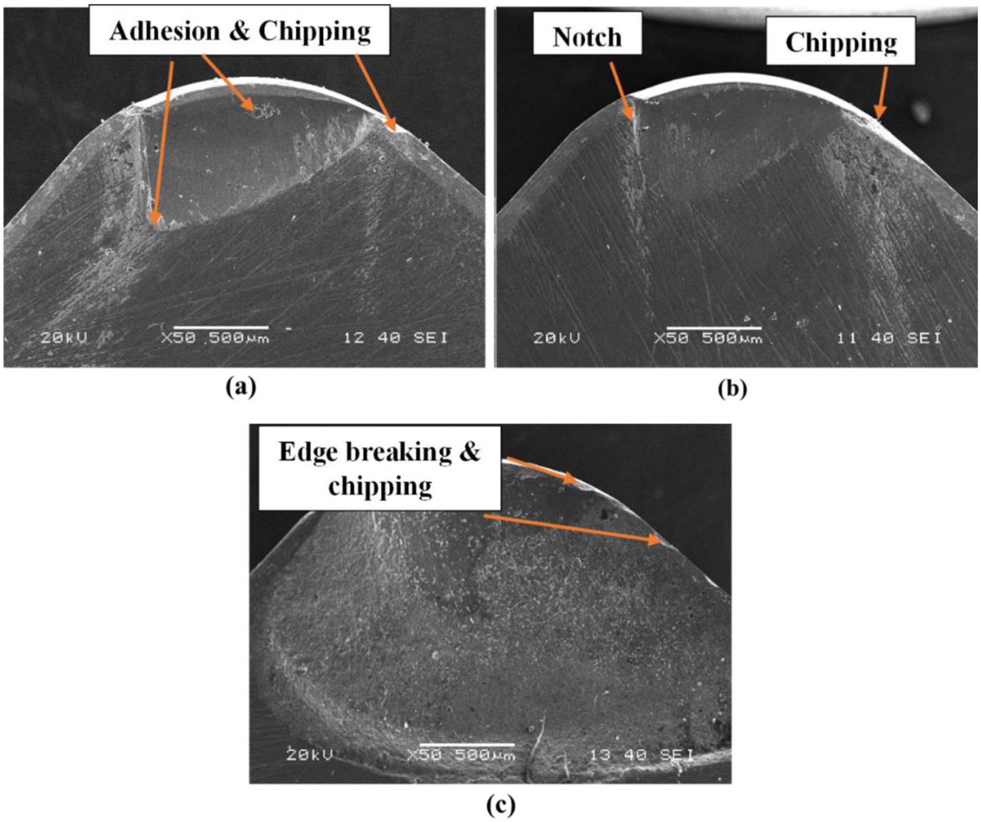


Fig. 3 Crater wear at cutting speed of 51 m/min and axial feed of: (**a**) 0.16 mm/rev, (**b**) 0.20 mm/rev, and (c) 0.24 mm/rev under dry cutting condition

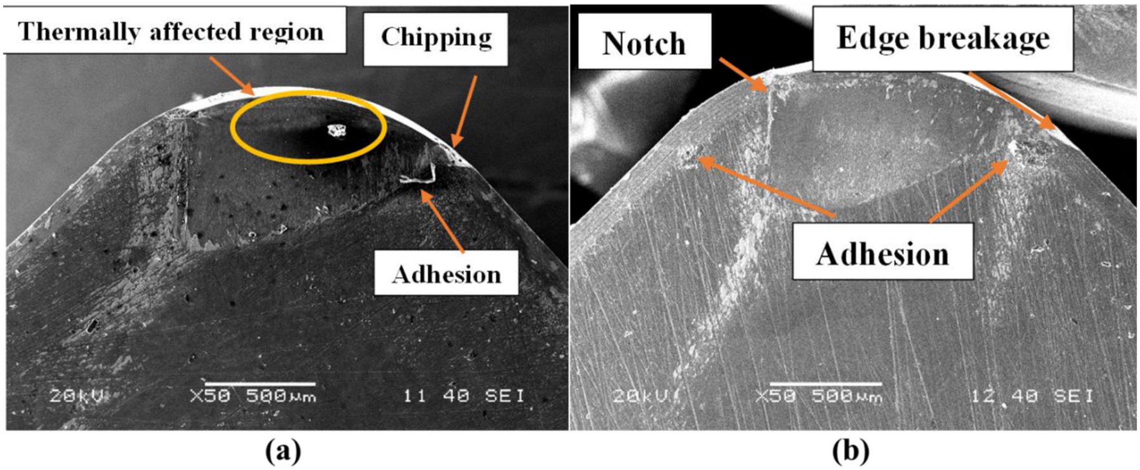


Fig. 4 Crater wear at axial feed of 0.12 mm/rev and cutting speed of: (**a**) 111 m/min, (**b**) 87 m/min under dry cutting condition

between workpiece and tool. In addition, very slight adhesion and chipping were noticed, as shown in Fig. 6.

The SEM micrograph of crater wear on SiAlON ceramic tool under flooded condition at three different cutting speeds (i.e. 111, 87, and 67 m/min) and constant low feed rate (i.e. 0.12 mm/rev) are shown in the Fig. 7. During high speed of 111 m/min and low feed of 0.12 mm/rev, temperature produced at tool-chip interface was high since there was less time to transfer heat and due to flood cooling at the tool-work contact zone high thermal gradient generated for which thermal cracks or chipping due to thermal stress occurred. But as speed value reduced the thermal damage also reduced. But when machining is performed at constant lowest speed (i.e. 51 m/min) and two different feed rates (i.e. 0.20 mm/rev and

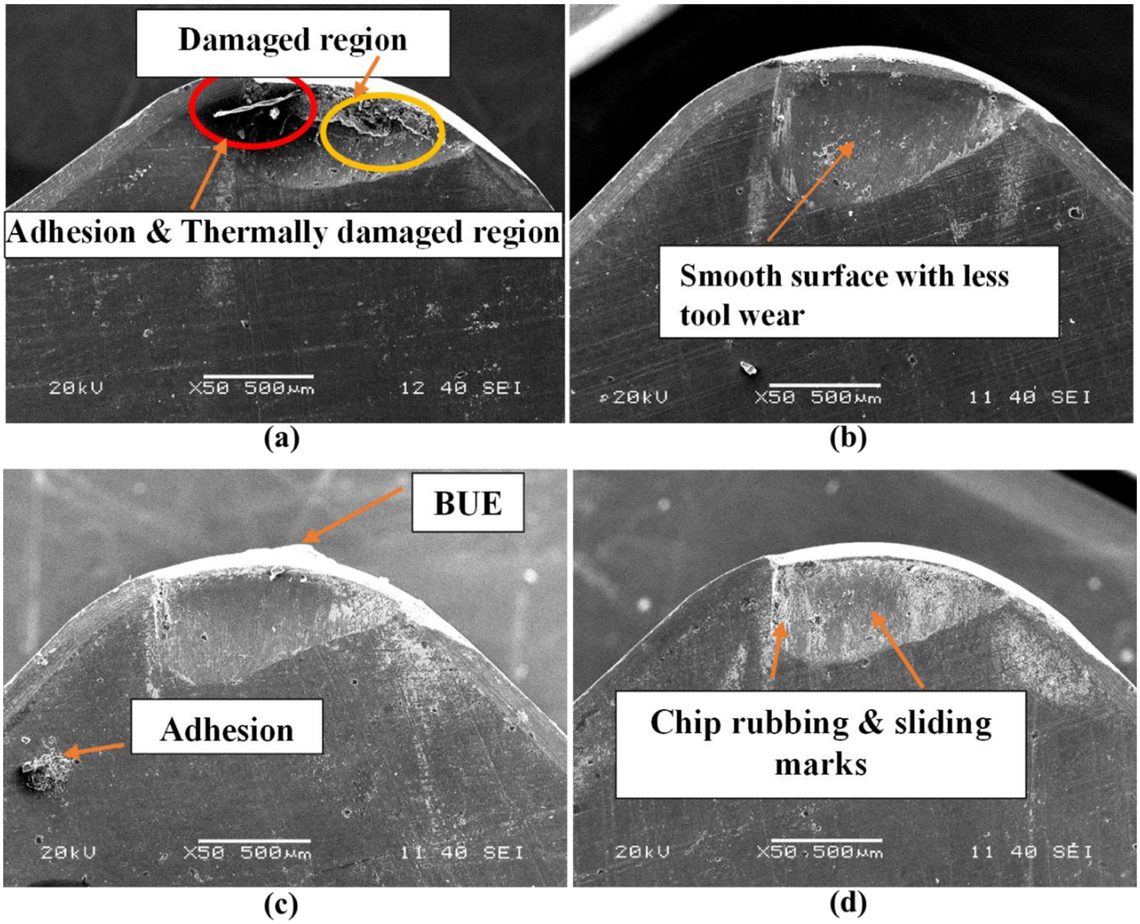


Fig. 5 Crater wear at axial feed of 0.12 mm/rev and cutting speeds of: (**a**) 111 m/min, (**b**) 87 m/min, (**c**) 67 m/min, and (**d**) 51 m/min under compressed air condition

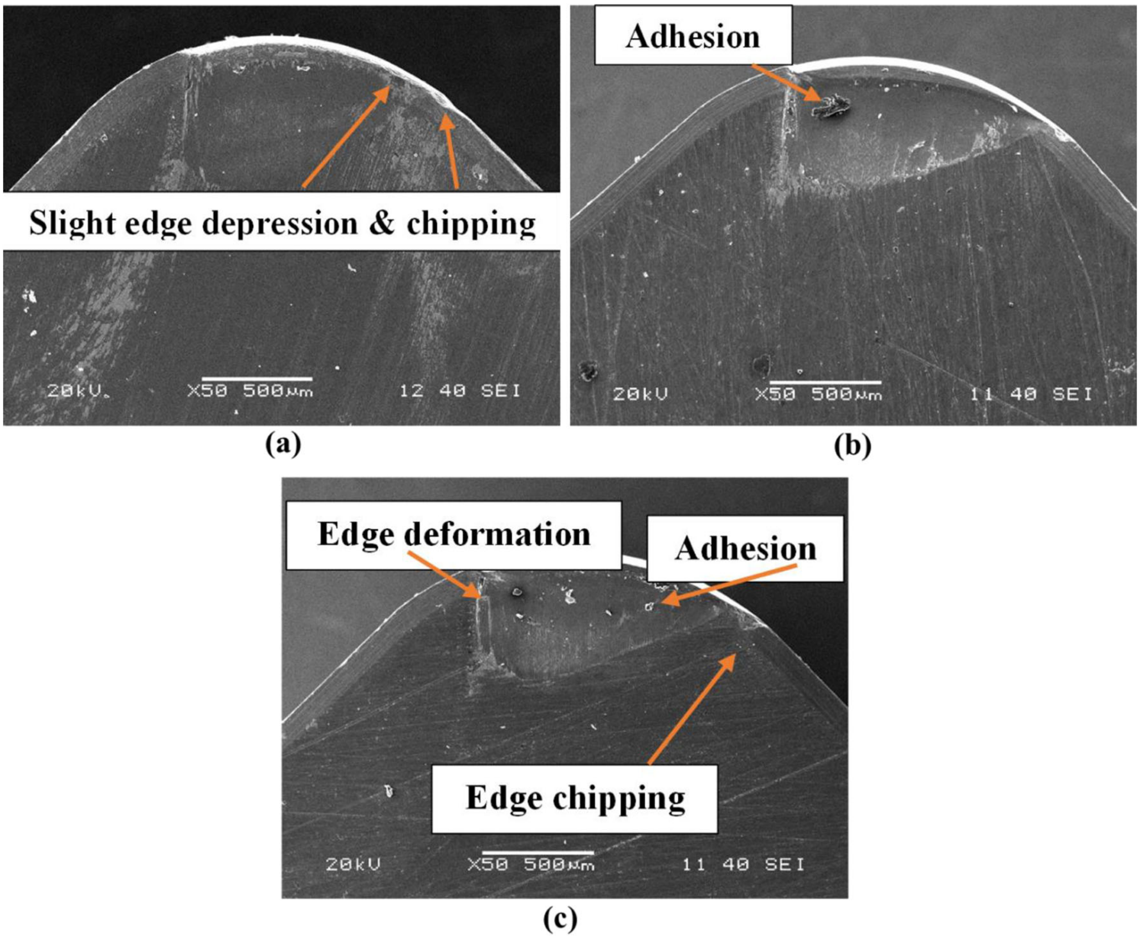


Fig. 6 Crater wear at cutting speed of 51 m/min and axial feed rates of: (**a**) 0.16 mm/rev, (**b**) 0.20 mm/rev, and (**c**) 0.24 mm/rev under compressed air condition

0.24 mm/rev), less wear as observed on rake surface (Fig. 8). As the contact time between tool and test specimen decreases resulting in less temperature generation. So, due to the application of flooded coolant, the amount of heat taken out from the workpiece and tool interface increases which leads to less thermal distortion and thus less wear observed on rake face of the tool.

Figure 9 represents the SEM micrograph of rake face of SiAlON ceramic tool under MQL condition at cutting speeds of 111 m/min and 81 m/min and constant axial feed of 0.12 mm/rev. due to the generation of high temperature at higher speed and lower feed rate condition, the burned region was observed on the rake face of the insert in the form of black spot. Along with burned region adhesion of the chip can also be seen which got adhered due to high temperature. The chipping observed was less than the other cutting environment because of the increase in the transfer of the heat. But some amount of chipping and breaking of the tool is still present. Due to the effective heat transfer from machining zone to the remaining part off the tool, the tool breakage was negligible. Adhesion is the common phenomenon which can be observed at high speed in all cutting environments. When feed was 0.24 mm/rev as shown in Fig. 10c, the damage region was less on the rake face but when the feed changed to 0.20 mm/rev, the damage region increased slightly shown in Fig. 10b because with less feed there will be more contact between the cutting edge and workpiece. So, rubbing between the tool and workpiece increases resulting in more friction and thus temperature which promotes thermal damage like adhered chip material, cracking, chipping, adhesion and diffusion. Similarly, in Fig. 10a one can see that the wear has increased because of the same reason.

After observing both wet and dry cutting conditions, it can be seen that more damage of rake face is visible under dry cutting condition than wet condition. Plastic deformation, adhesion, and BUE formation are the major modes of tool wear. Higher chemical affinity and lower thermal conductivity of machined part might have contributed to this. Crater wear was examined in four cutting conditions (i.e dry, compressed air, flooded and MQL) at different combination of speed and feed by keeping doc constant throughout the experiment. From Fig. 11a, it was observed that crater wear has increased

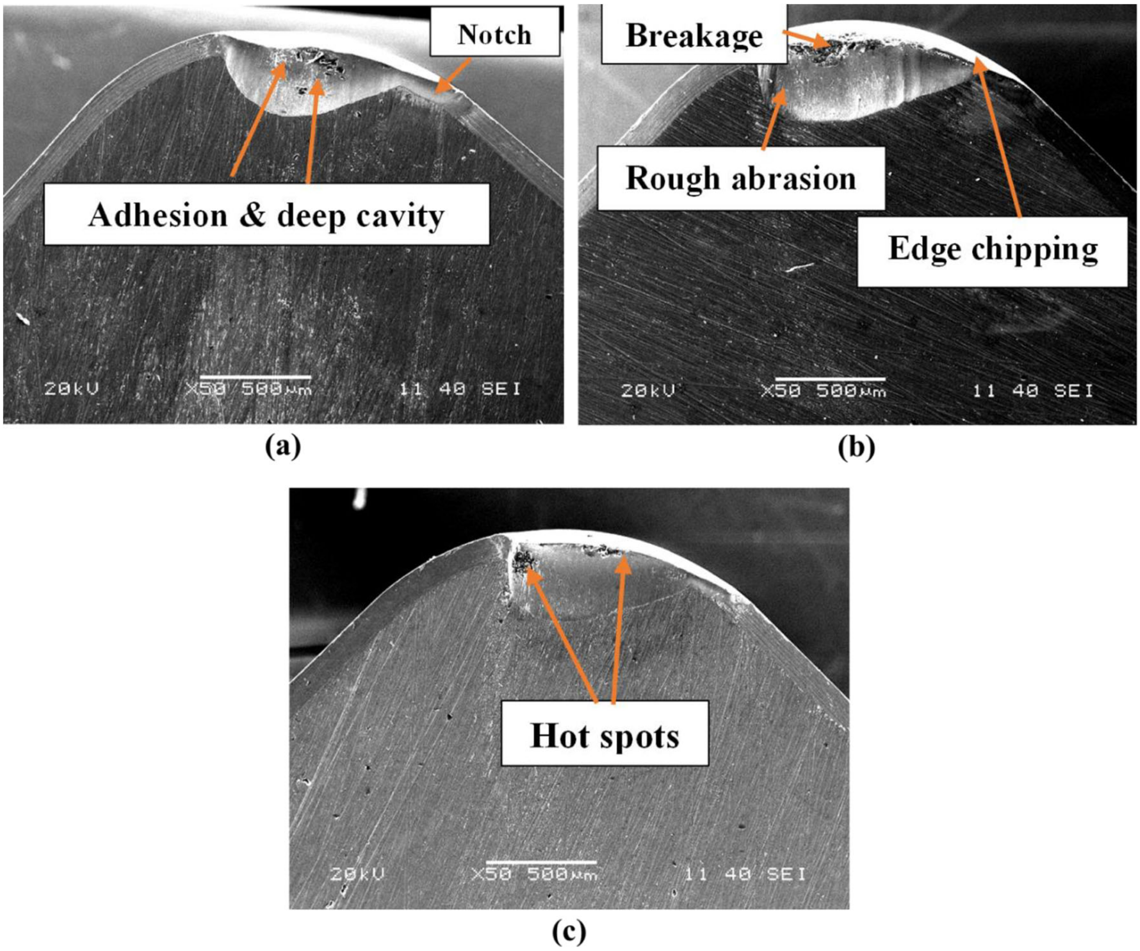


Fig. 7 Crater wear at feed rate of 0.12 mm/rev and cutting speed of: (**a**) 111 m/min, (**b**) 87 m/min, and (**c**) 67 m/min under flooded condition

with increase in cutting speed when feed and depth of cut kept constant. From optical micrograph of rake face of SiAlON ceramic tool, it was observed that maximum crater wear was observed at high speed (i.e. 111 m/min) and low feed condition (0.12rev/s) in all cutting condition. It was also noticed that the crater wear increases with decrease in feed rate when cutting speed was kept constant at its lower value as shown in Fig. 11b. However, minimum wear was observed in MQL cutting condition than other cutting condition. Because due to the effective jet propulsion of coolant in MQL, the lifting

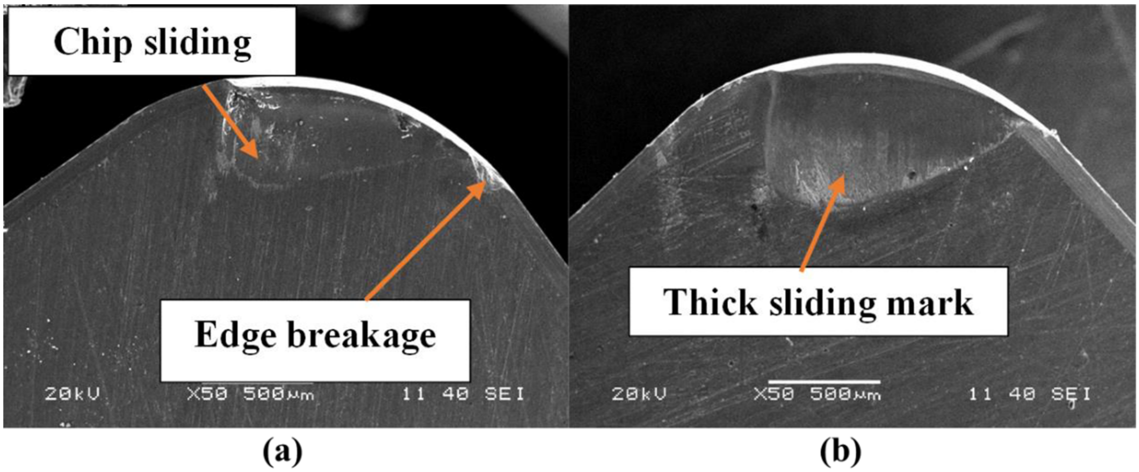


Fig. 8 Crater wear at cutting speed of 51 m/min and feed rate of: (**a**) 0.24 mm/rev, (**b**) 0.20 mm/rev under flooded condition

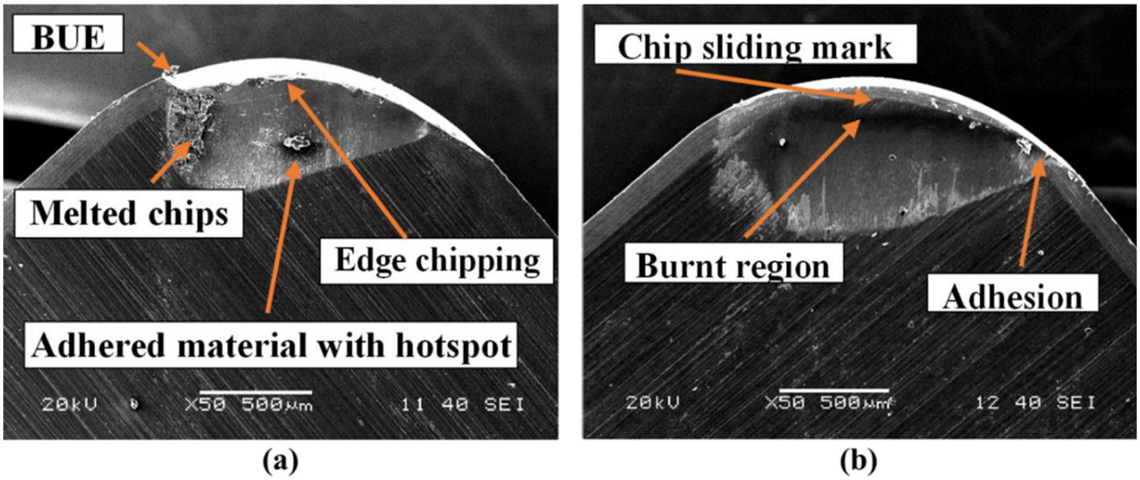


Fig. 9 Crater wear at axial feed rate of 0.12 mm/rev and cutting speeds of (**a**) 111 m/min, and (**b**) 81 m/min under MQL condition

of the chip was observed for which the wear area on rake surface was diminished. The tool-chip contact length plays an important role, with high tool-chip contact length and more damage in rake face.

For EDS analysis, the surfaces of the tool were magnified and the phenomenon of transfer of workpiece material on the tool can be seen. Also, it can be observed that the deposition of work material is maximum in dry cutting condition and minimum in MQL condition. This may be because of the amount of heat generated at chip-tool interface is high in the dry condition which leads to adhesion of the work material on the tool rake face. As shown in Fig. 12, it can be clearly seen that the

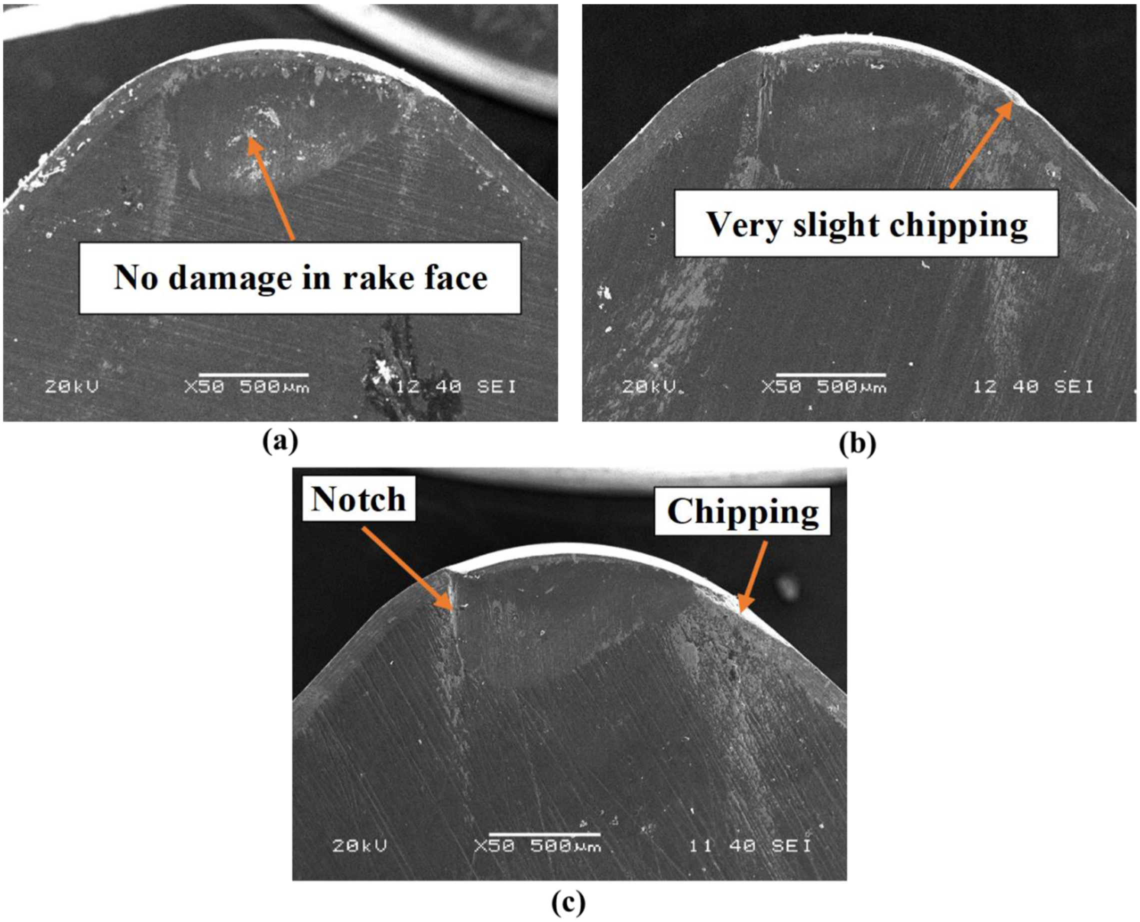
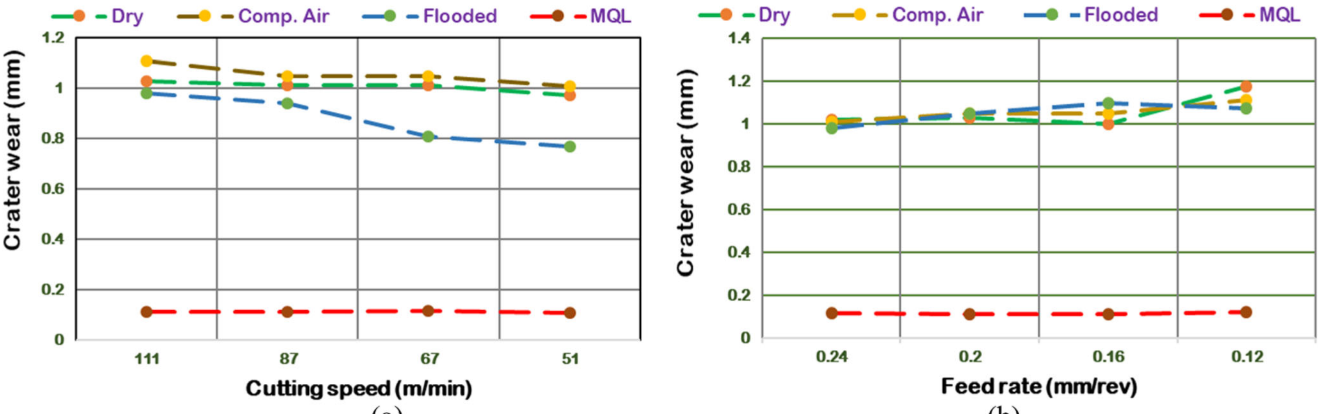


Fig. 10 Crater wear at cutting speed of 51 m/min and feed rate of (**a**) 0.24 mm/rev, (**b**) 0.20 mm/rev, and (**c**) 0.16 mm/rev under MQL condition

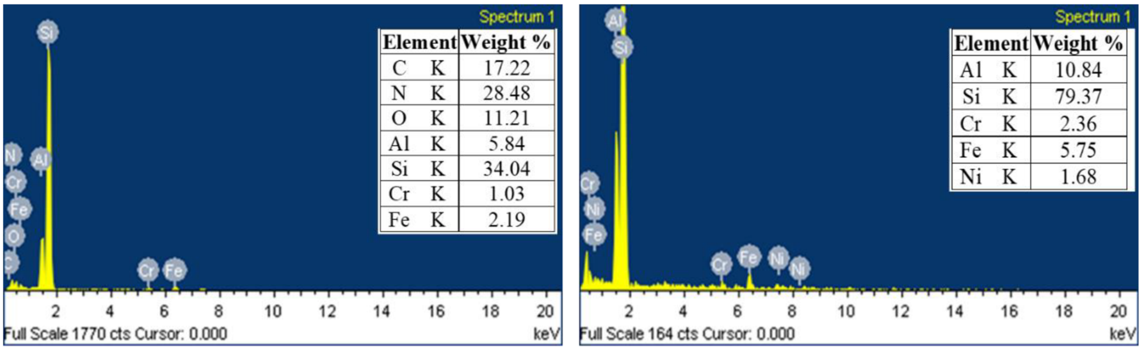


(a) (b)

Fig. 11 Variation of crater wear (**a**) with cutting speed at feed rate of 0.12 mm/rev, and (**b**) with feed rate at cutting speed of 51 m/min

diffusion of work material is more in dry cutting condition than in MQL and flooded cutting conditions. In dry cutting condition, in the selected spectrum, nickel, chromium and iron were found combined around 26% and that in flooded and MQL cutting conditions are 10% and 4% respectively. The diffusion of work material takes place more in dry cutting condition because of the generation of more temperature at chip-tool interface.

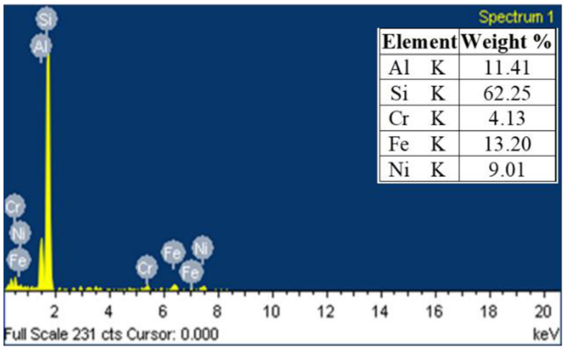
Optical images of the tool at cutting speed of 51 m/min and at an axial feed rate of 0.20 mm/rev are shown in Fig. 13. It shows sticking and sliding phenomena on rake surface of the tool. If observed carefully, the region on the rake face has two zones. Zone 1 which is along the principal cutting edge and nearer to insert's nose which indicates the region of extreme adhesion which is caused by the higher stress level. Abrasion is the cause for the formation of zone 2 where gradual wear takes place. The wear in this zone takes place because of chipping. Some fragment can also be seen in this zone which is confirmed by EDS analysis. It is observed that when cutting speed increases the length of the zone 1 decreases. Out of four stratergies of cutting environment, MQL technique shows the effective cooling-lubrication behaviour due to reduction in crater wear in terms of lower sticking and sliding zone.



Element		Weight %
C	K	17.22
N	K	28.48
O	K	11.21
Al	K	5.84
Si	K	34.04
Cr	K	1.03
Fe	K	2.19

Element		Weight %
Al	K	10.84
Si	K	79.37
Cr	K	2.36
Fe	K	5.75
Ni	K	1.68

(a) MQL (b) Flooded



Element		Weight %
Al	K	11.41
Si	K	62.25
Cr	K	4.13
Fe	K	13.20
Ni	K	9.01

(c) Dry

Fig. 12 EDS spectra and composition in the different cutting environments at cutting speed of 111 m/min

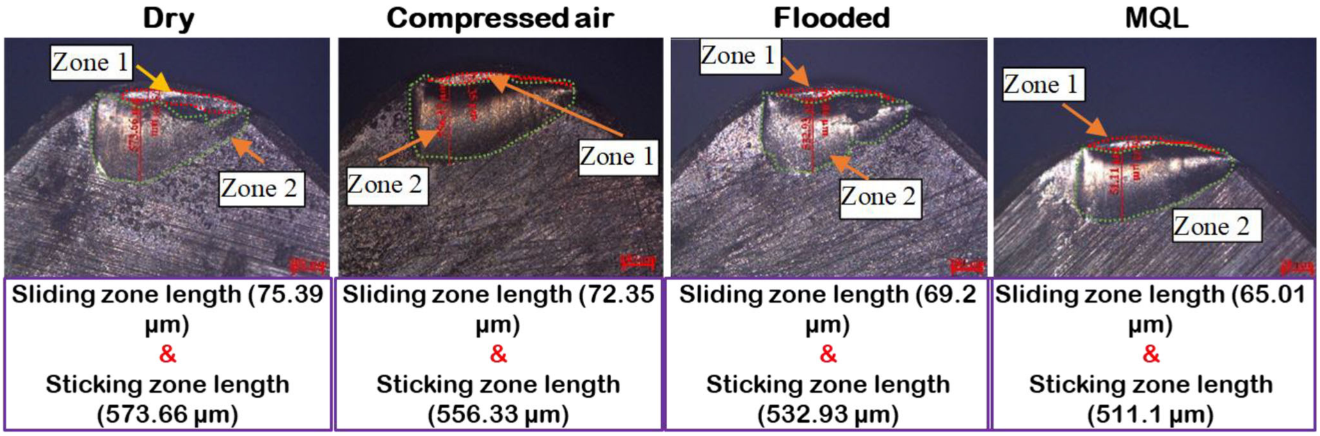


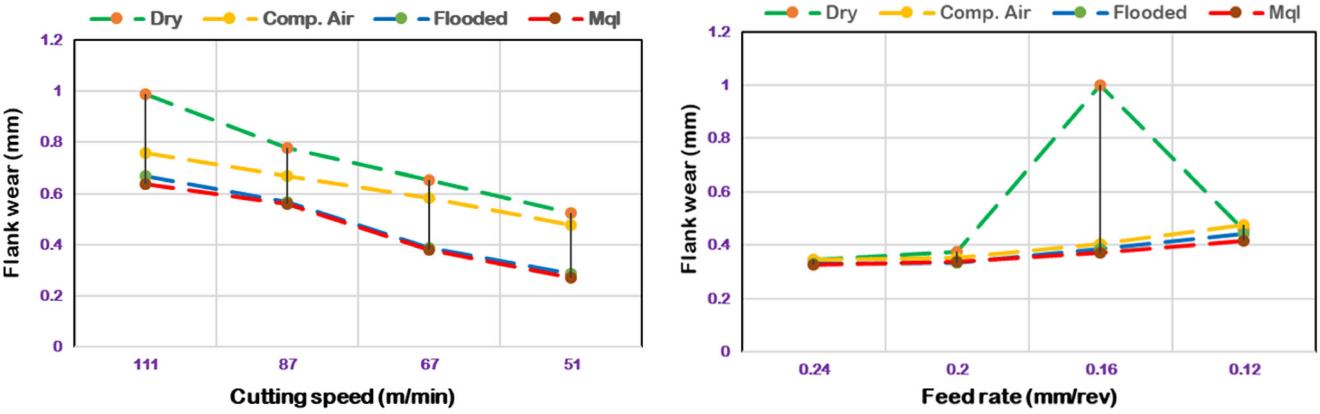
Fig. 13 Sliding and sticking zone lengths at cutting speed of 51 m/min and feed rate of 0.20 mm/rev

3.2 Flank Wear Analysis

Flank wear is mainly analyzed at two cutting speeds i.e., 111 m/min and 51 m/min at constant feed rate of 0.12 mm/rev in all four-cutting environments. As shown in Table 5, at high cutting speed the wear on tool flank surface is maximum by various mechanisms such as adhesion, plastic deformation, notching, chipping and edge deformation. The main reason for the wear was temperature generation which is high while cutting at high speed specifically in dry machining condition. Also, deep notches were observed in dry cutting condition at high cutting speed. But in case of low cutting speed, smooth abrasion with slight chipping was found. Chipping can be seen in both low and high cutting speed and mostly depends on the environment chosen. Plastic deformation is generally not observed during machining at low speed since the temperature required for plastic deformation is high. Furthermore, flank wear also tends to increase with the increase in cutting speed (see, Fig. 14a) at all cutting condition, while a very slight change in flank wear width was noticed with increase in feed rate (refer, Fig. 14b) at all cutting environment except dry cutting condition. A similar result also observed by Ramanuj Kumar et al. [24]. In both high and low cutting conditions, it is observed that flank wear changes from one cutting environment to another. Dry cutting environment shows the maximum wear and the MQL shows the least. This might be because of the difficulty in heat dissipation in the dry cutting and effective cooling and lubrication in MQL. In MQL, very smooth abrasion, less adhered material as well as BUE formation, very less chipping and compact notch were observed. Better results were observed in compressed air compared to dry cutting condition.

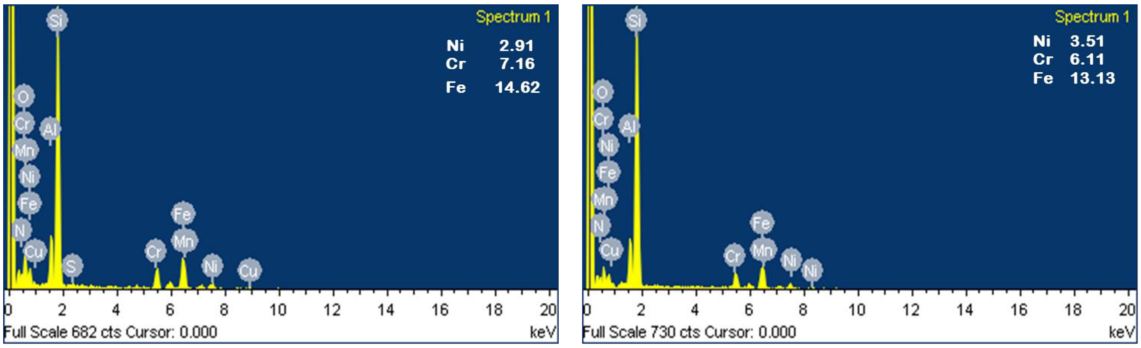
Table 5 Flank wear at different cutting speeds and constant feed of 0.12 mm/rev under various cutting environments

The EDS analysis of flank surface SiAlON ceramic tool after machining at a cutting speed of 111 m/min at different cutting environment have been represented in Fig. 15. It can be observed that the deposition of work material is maximum in dry cutting condition and minimum in MQL condition. It may be due to the macro diffusion of workpiece material in to

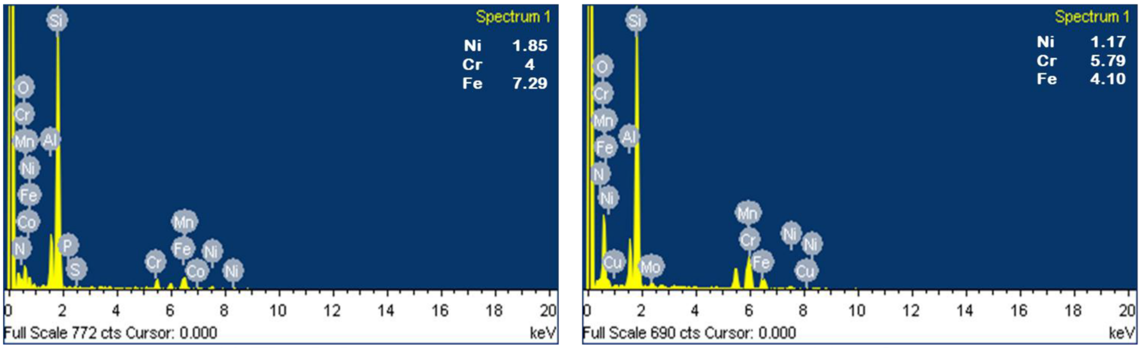


(a) (b)

Fig. 14 Variation of flank wear: (a) with cutting speed at axial feed of 0.12 mm/rev, and (b) with feed rate at cutting speed of 51 m/min



(a) Dry **(b) Compressed air**



(c) Flooded **(d) MQL**

Fig. 15 EDS spectra and percentage composition in the different cutting environments at cutting speed of 111 m/min

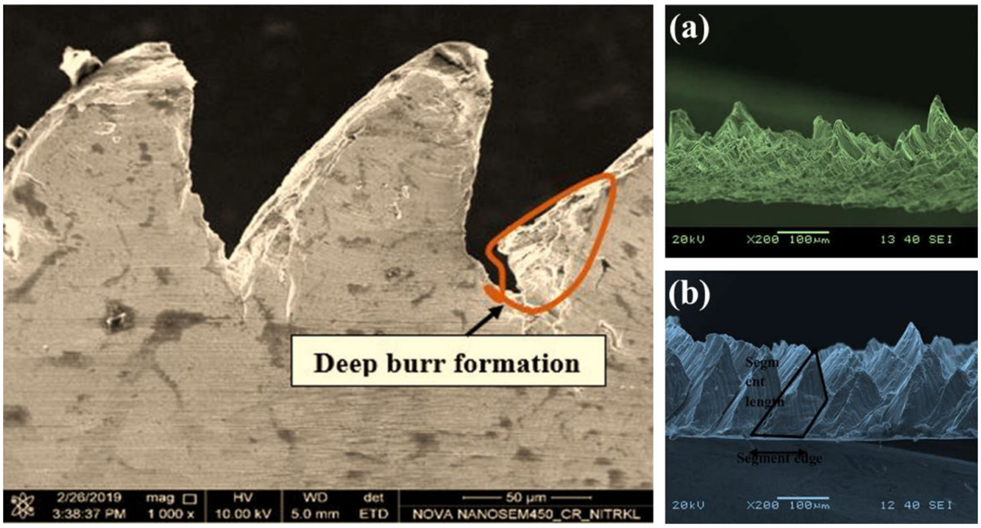
the tool during the dry turning as high heat is generated at higher cutting speed. In dry cutting condition, in the selected spectrum, nickel, chromium and iron are combinedly around 25% and that of flooded and MQL cutting conditions are 13% and 11% respectively.

3.3 Nose and Notch Wear Analysis

Severe nose wear was observed at the nose part of the insert in the dry cutting condition. The nose wear was due to improper cooling and lack of lubrication in dry machining environment. At high cutting speed, the thermal cracking was observed due to the generation of high temperature. Moreover, a huge amount of chip fragments was observed during machining of Nitronic 60 super alloy in dry cutting circumstances. The micro fracture was also noticed on the insert's surface in dry cutting condition due to the combinations of some influential factors such as strain hardening, diffusion and thermal cracking. SiAlON ceramic cutting inserts are very hard and brittle but have low toughness for which during the machining with such inserts fails due to notch wear. However, SiAlON ceramic inserts possesses very good toughness, better abrasive resistance and low chemical affinity.

The chip morphology is an important criterion for the notch wears mechanism of the ceramic insert, because the saw tooth chip formed during the machining of difficult as well as hard-to-cut materials at the end of the cutting zone forms a notch. During turning process of hard and difficult-to-cut materials, high compressive stresses are experienced due to negative rake angles of the cutting tools [33] which lead to the formation of cracks and plasticization due to the brittleness of the hardened steel, occurs at the chip's primary shear plane, resulting serrated chips. These cracks start on the chip's free surface and go deeper towards the tool nose, relieving the energy stored and acting as a sliding surface for the material segment [34]. Simultaneously, heating and plastic deformation of the material occurs at the leading edge of the cutting tool. The process repeats itself in a cyclic manner after the chip segment has slipped with another new formation of crack and chip segment results in formation of saw-tooth chip [35]. The friction and burr formation on saw-tooth chip are the main reason for the notch wear. In the present experimental investigation, burr was noticed on the chip surface as presented in Fig. 16. Burr formation during machining greatly influenced the notch formation in the tool flank face. The irregular burr formation generates friction between tool-chip and work-tool interfaces at the cutting depth. This friction along with the combined effect of diffusion and oxidation affect the abrasion resistance of the tool, which creates a suitable situation to form the notch on the tool flank face. Tool geometry also plays a crucial role for this burr formation. More burr generally produced with negative inserts. The burr formation on the chip surface is the evidence of the work-hardening of the material, which influenced the notch wear in cutting depth

Fig. 16 Burr formation in (**a**) MQL cutting condition, and (**b**) dry cutting condition



at the cutting edge of the insert. Welding and adhesion were also found to be the major factors for notch wear during the machining of Nitronic 60 super alloy.

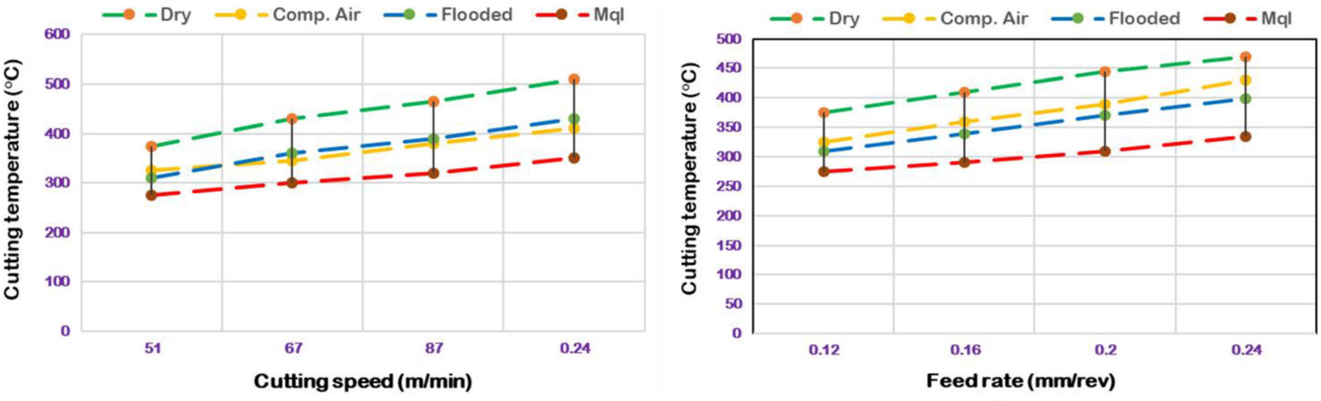
Notch wear was observed to be the primary wear pattern for the cutting inserts. Out of four cutting environments, dry cutting was found to be harsher than the other cutting conditions. In dry cutting condition, notch wear was found to be expanded towards the principal cutting edge. But in MQL, the wear was restricted to the nose area.

3.4 Cutting Temperature Analysis

During the machining process, an adequate amount of energy was involved in chip removal process which results in considerable amount of heat generation at cutting zone. So, it caused to increase the temperature at the tool-chip interface. So, cutting temperature is also a vital aspect to evaluate the machinability. Because, high interface temperature may produce some unavoidable condition such as tool wear, plastic deformation of the cutting edge and heat affected zone at workpiece. It also affects the dimensional accuracy and surface quality of the product. In this work, the influence of different cutting condition (i.e. dry, compressed air, flooded and MQL) and cutting parameter (i.e. cutting speed and axial feed) on cutting temperature was evaluated. Different cutting temperatures were measured from the laser IR gun by pointing the laser at machining zone. Higher temperature was noted in dry condition as compared to others whereas lowest interface temperature was observed in MQL condition as shown in Fig. 17a and b. Figure 18 shows the comparison among all four-cutting conditions at different cutting parameters. During machining with different cutting parameters, it can be noted that MQL shows better results in each experimental run. Reduction in chip-tool contact length while using MQL is the reason behind lower temperature generation.

3.5 Cutting Force Analysis

Cutting force is a crucial aspect to evaluate the machinability of difficult-to-cut material. During any machining operation, cutting force is the key aspect to calculate the energy consumption and power requirement of the machine tool, which



(a) (b)

Fig. 17 Variation of cutting temperature with: (**a**) cutting speed of at feed rate of 0.12 mm/rev, and (**b**) with feed rate at cutting speed of 51 m/min

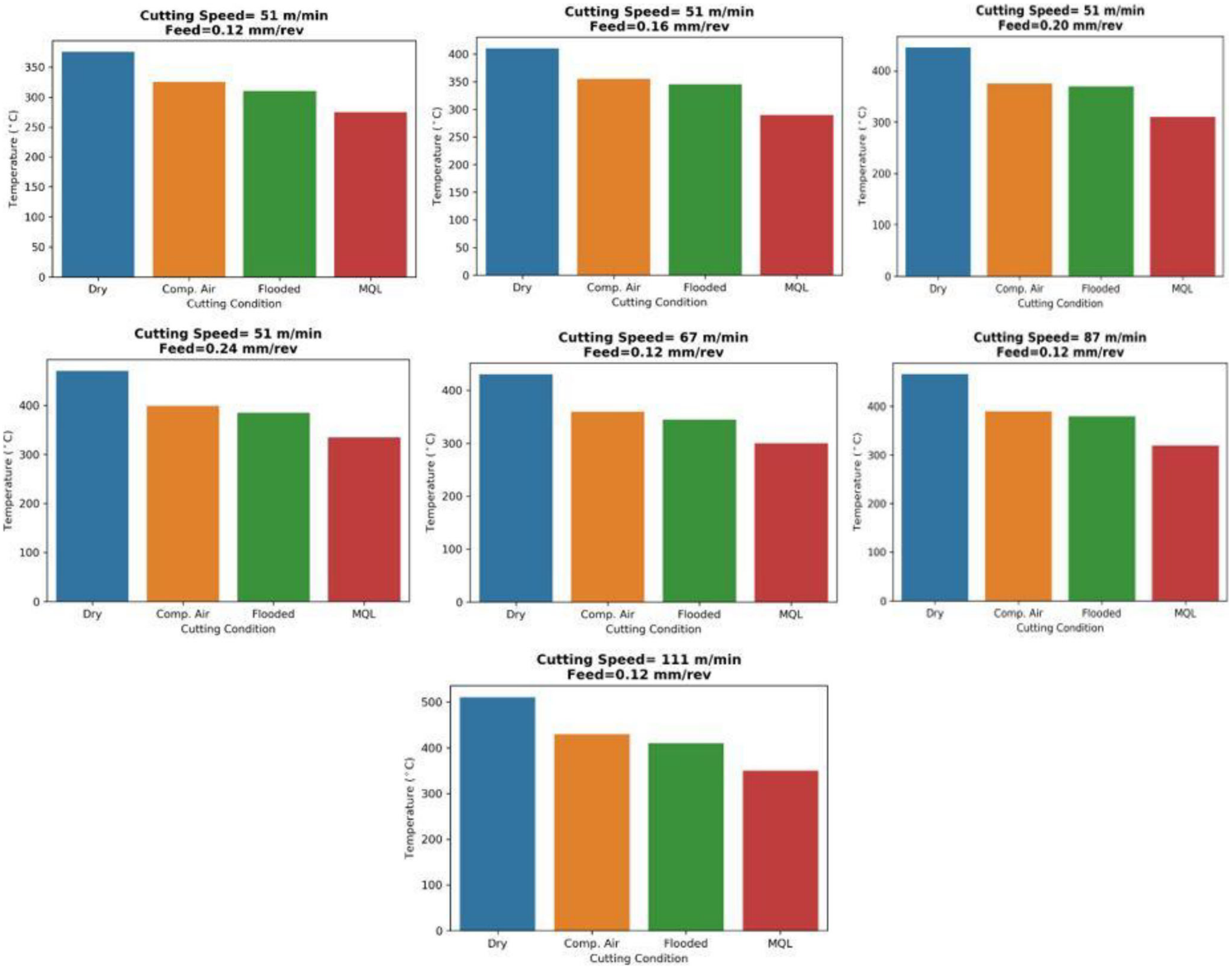


Fig. 18 Variation of cutting temperature at different machining conditions under various cooling-lubrication techniques

is affected by various factors like tool wear, friction at chip-tool interface, thermo-mechanical properties of tool and workpiece material, tool material and tool geometry, cooling environment and method of application of coolant [36]. Cutting force is also an imperative tool to control different output characteristic such as thermal aspects in machining, deformation characteristic of tool and workpiece, dimensional deviation, chip formation, surface finish and tool life [37]. In this work, experiments have been proposed to analyze the influence of cutting parameters (cutting speed and feed rate) and different cooling condition on cutting force. Figure 19 shows the variation of cutting force in different cutting environments. It is noticed that the cutting force is minimum in MQL condition than other cutting environments. In machining of Nitronic 60 sing SiAlON ceramic tool, analysis of cutting force is performed by considering the results of seven experimental trails into two groups. The first group in which the feed rate has been kept constant with cutting speed varying in four steps while in the second group, the cutting speed has been kept constant with the feed varying in four steps. From the group one, Fig. 20a illustrated that, irrespective of cooling environment cutting force tends to decrease with increase in cutting speed. This is because of the increase in the temperature at chip-tool interface along with increase in the cutting speed leads to thermal softening thereby resulting decrease in the force required for cutting. Moreover, high speed machining also lowers the shear strength of workpiece material and thus reduces the cutting force. Hegab et al. [38] stated that the increase in chip flow at high speed may decrease the cutting force by reducing the co-efficient of friction. After studying the group two, Fig. 20b illustrates that, with increase in axial feed rate and considering the cutting speed constant (51 mm/rev), resulting in enhancement of cutting force. This result is expected at higher feed due to work-tool contact time is less leading to higher chip area and resistance to shear deformation which results in higher cutting force.

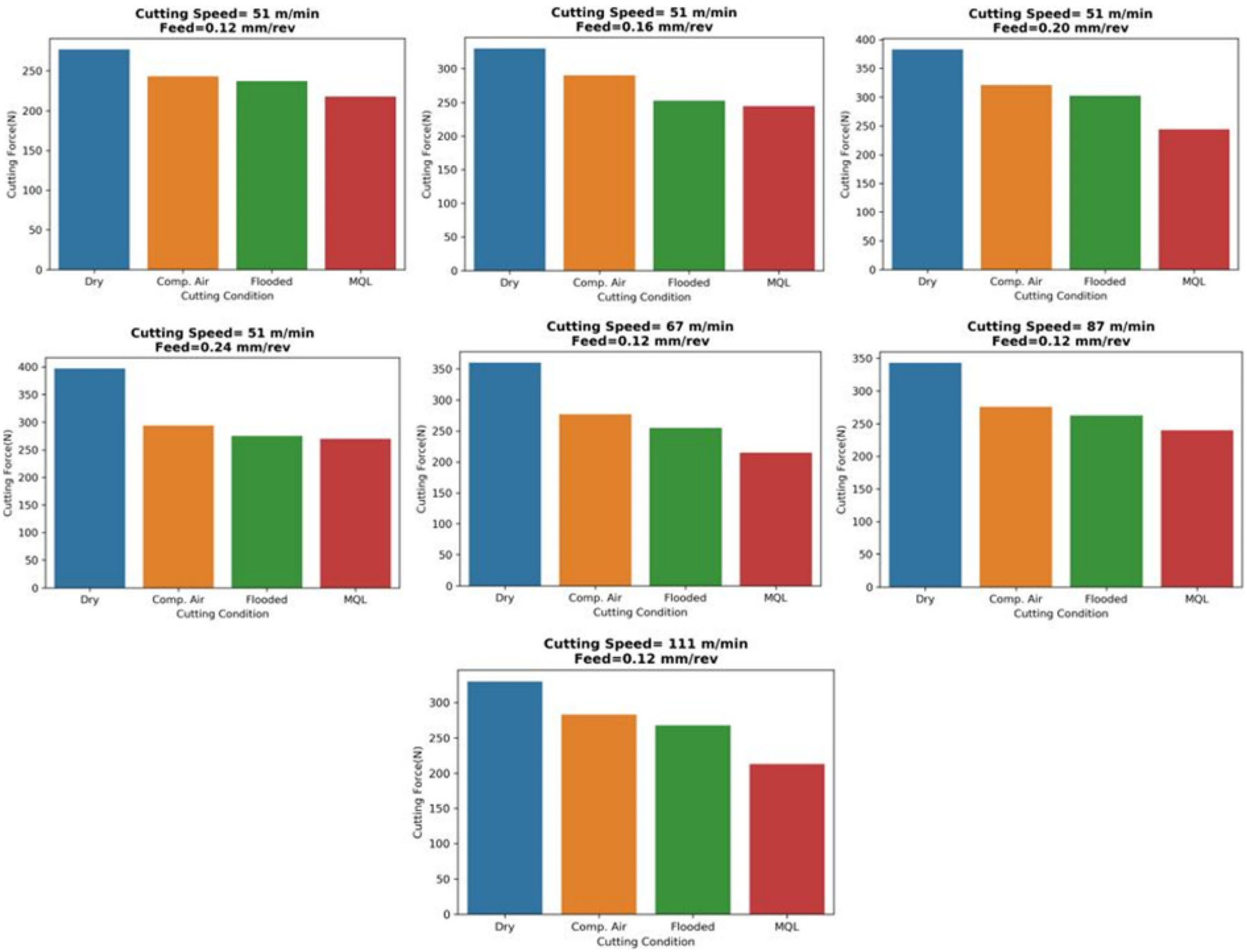
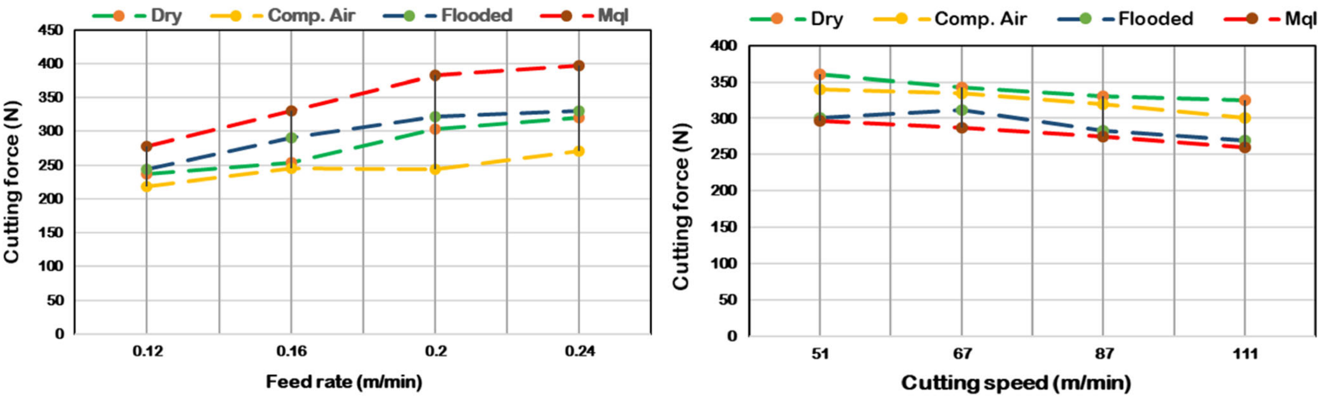


Fig. 19 Variation of cutting force at different cutting parameters under various cooling-lubrication techniques

3.6 Machined Surface Roughness Analysis and its Morphology

Fatigue life of a machined component is very pivotal. Many factors such as cutting variables, materials, shape and geometry of the tool material, wear pattern of the tool material and work-piece material are responsible for the service life of a machined component. In present experimental investigation, turning of Nitronic 60 was accomplished in four cutting environments like dry, compressed air, flooded and MQL. Out of



(a) (b)

Fig. 20 Variation of cutting force: (a) with feed rate at cutting speed of 51 m/min, and (b) with cutting speed at feed rate of 0.12 mm/rev four cutting environments, a maximum surface defect was found in dry and compressed air conditions. Because in both the above-mentioned conditions, the machined surface might be subjected to high temperature and mechanical stress, which induced the surface defects like feed marks, debris, side flow, re-deposited material, surface plucking, thermal damage, tool rubbed surface, hot spots etc. The all surface defects are present with layer dimension with high density, as shown in Fig. 21. The SEM images of tool rake face while machining Nitronic 60 using SiAlON ceramic under various cutting environments were exhibited. Due to high chemical affinity of the material, some material was adhered to the tool rake face, which formed the built-up-edge. This BUE formation is due to high friction as observed while machining in dry environment condition at low cutting speed. The SEM images also designate that the propensity of BUE formation in dry cutting condition was more eminent compared to flooded and MQL conditions. Due to this BUE formation, the surface defect was found to be maximum in dry cutting condition. The above surface defects normally occurred due to various causes. But one interesting phenomenon was observed, when speed increased to 87 m/min, unwanted damage on machined surface was not observed. Due to continuous machining, there is a chance of rapid tool wear, so due to rapid wear of the insert there may be a chance of re-deposited material and debris on the machined surface as clearly observed in Fig. 22. Marvelous cooling and lubrication technology involved in MQL diminished the friction during machining, resulting better tool performance, which enhanced the machined surface morphology. Sometimes surface oxides shown in Fig. 23a act as a thin lubricating film, this might be a reason for this phenomenon. With use of lubricant in MQL and flooded it was obtained good surface finish compare to dry and compressed air at same cutting parameters. Smooth surface is present in MQL and flooded, as shown in Fig. 23b.

It is obtained from current study that surface roughness decreased with increasing cutting speed at constant feed rate and depth of cut, as shown in Fig. 24a. Feed rate has also a crucial influence on the surface quality of the machined component. Roughness increased with feed for all the cutting environments, as shown in Fig. 24b. This phenomenon can be attributed to: (i) the formation of broader and deeper helicoid furrows on the machined surface (left by insert's nose-shape and the relative movement of workpiece-tool combination) by ploughing action [39], and (ii) well established relationship of geometrical arithmetic mean roughness with the cutting parameters, feed and corner radius of tool by the expression $Ra = 0.0321f^2/r$ [18, 40]. Moreover, it is observed that, with increased axial feed under dry and compressed air cutting condition creates vibration and heat generation with an evolution of undesirable thrust forces thereby resulting degraded surface finish of machined part in terms of thick feed marks with rubbed surface, as clearly noticed in SEM observation (refer, Fig. 25). Similarly, in MQL condition, with the increase in the feed, the cutting time reduced and shear plane area of chip increases which results in material accumulation in the form of chips at tool-work-chip interface. Hence increased friction led to deterioration of machined surface in accordance with a previous study [41]. In MQL and flooded conditions, tool-chip temperature is less which results in improved surface finish as compared to dry and compressed air cutting conditions.

3.7 Sustainability Assessment

In any manufacturing industry, sustainability plays a vital role to integrate economical, environmental and social prospective with supply chain management system. In particular, sustainability assessment of every production technology is very prominent perspective, prior to its

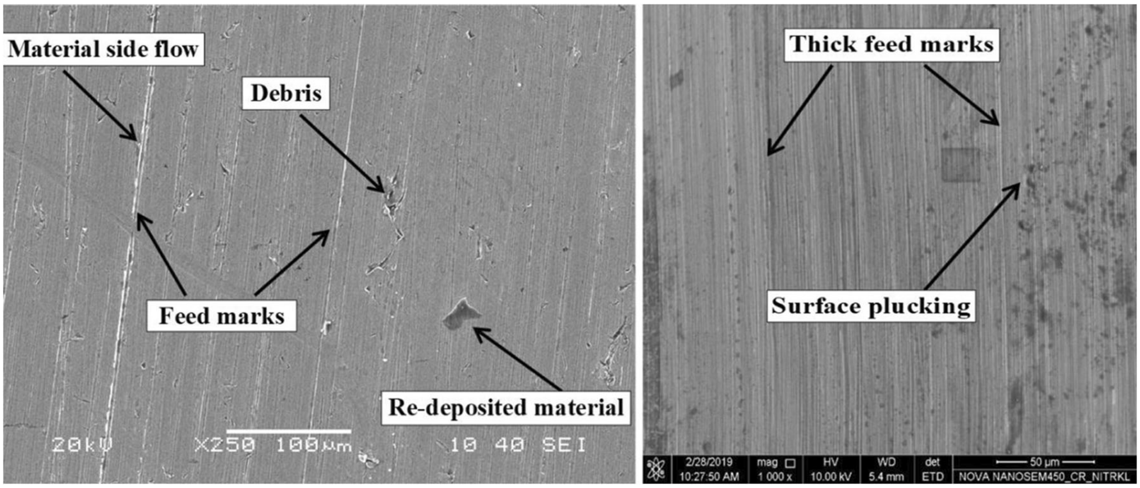


Fig. 21 Surface defect under dry and compressed air cutting conditions

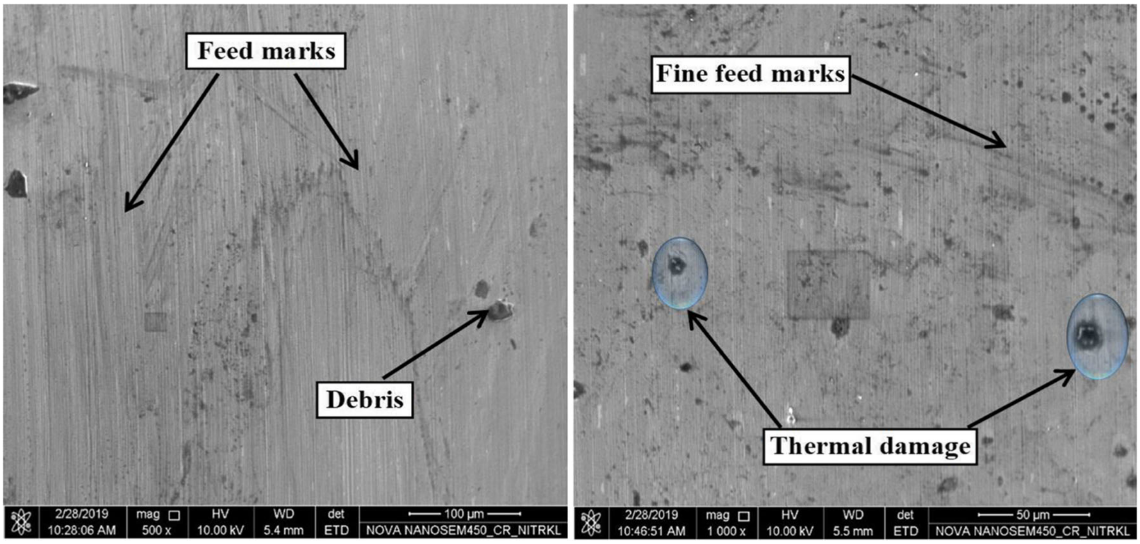


Fig. 22 **a** Surface roughness found due to rapid tool wear, **b** Unwanted damage on machined surface

adoption in industry for safer and cleaner manufacturing. The term "sustainable manufacturing" encourages adopting new environmental-friendly technologies as well as economically-sound processes with a broader social implication which promotes eliminating production and processing wastes, minimizes negative environmental impacts while conserving energy, and enhances employee health and safety through eco-efficient practices. Sustainable manufacturing is effective to justify the existence of production methodology by various parameters such as production cost and rate, cutting quality, process management, water and energy intensity, material waste management, environmental regulation, worker health and safety, labour relations, training and education. In the present work, sustainability assessment of machining process under various cooling environment-lubrication conditions is performed concerning technological, economical, and ecological aspects.

In the present study, sustainability of finish turning process under different cooling strategies is assessed by considering environmental effect, operator safety, coolant cost, part cleaning, coolant recycling and disposal, noise level, surface roughness and cutting temperature. For this, a decision-making effective technique called Pugh matrix is employed for sustainability assessment by assigning specific weight in terms of mathematical number for the abovementioned sustainable manufacturing parameters. The weight criteria are allocated to each quality parameter in the range from −2 to 2 based on its importance, i.e. "+1" and "−1" have been assigned for better and worse results respectively, whereas "+2" is given for much superior results and "−2" for much inferior results. At last all the assigned values are added for each cooling-lubrication (C/L) technique and the technique which scored highest value is selected as best criterion. Table 6 represents the score assigned to different C/L techniques

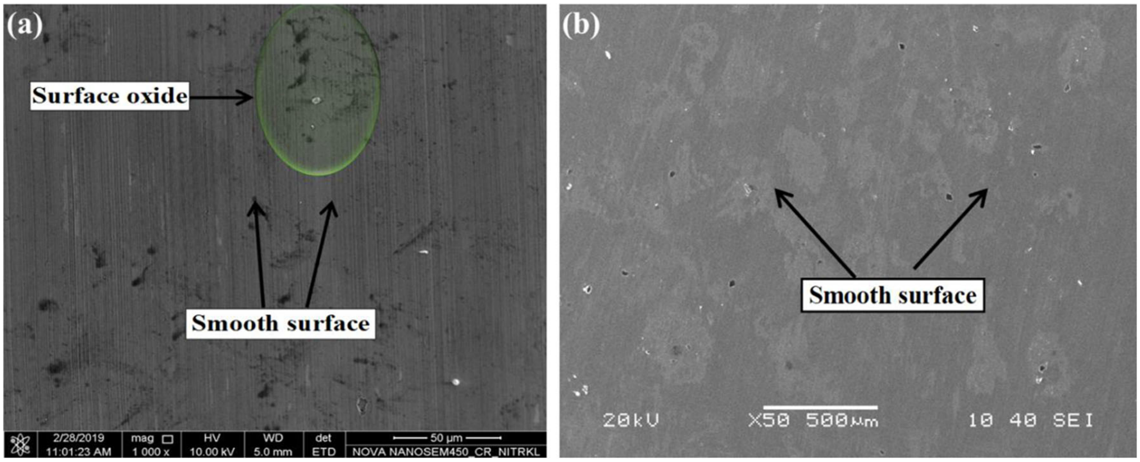


Fig. 23 Smooth surface is present in MQL and flooded conditions

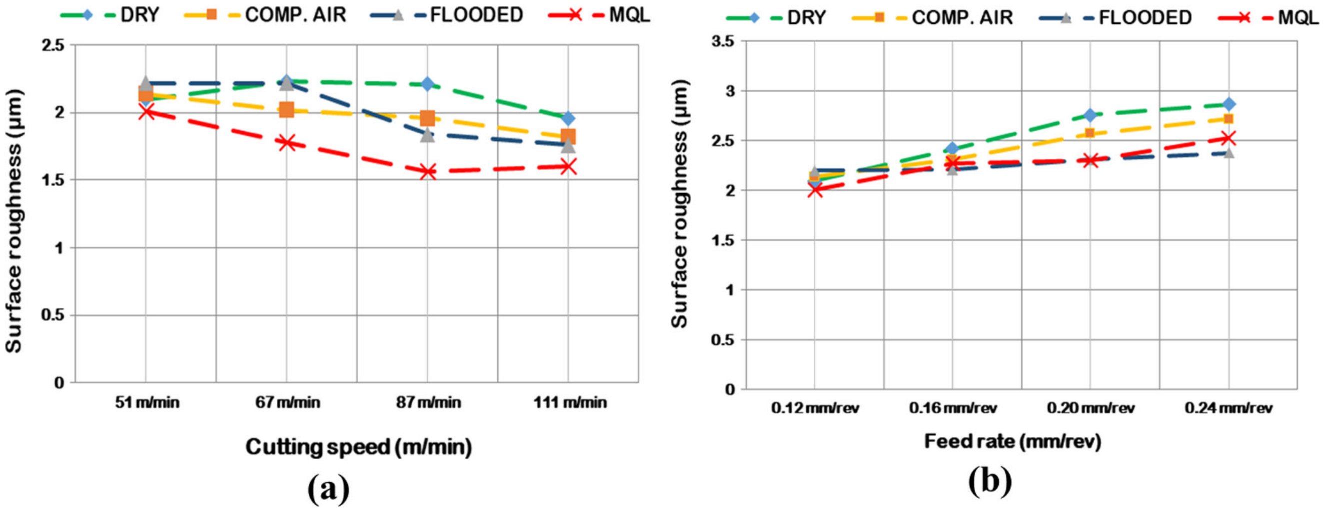


Fig. 24 Surface roughness: (**a**) with increase in cutting speed at constant feed rate of 0.12 mm/rev, (**b**) with increase in feed rate at constant cutting speed of 51 m/min

for the different selected criterion. When considering the environmental effect, a weight of “2” has been allocated to both dry and compressed air condition as no cutting fluid is used in dry and compressed air condition. Without using the cutting fluid, the operator health and environment is free from any harmful effects eligible to obtain score of “2” as well. Whereas a score of “-2” has been assigned to flooded condition, since excessive amount coolant is used which contains lots of harmful chemical constituents also emitted so harmful emissions to the environment during the operation. However, a very little amount of coolant with high speed compressed air (i.e. almost approach to near dry) is used in MQL condition. So, it emitted very less amount of harmful emission obtains a score of “−1”. To evaluate the sustainability assessment score for factor worker safety, authors have considered two parameters mainly exposure to high energy component and operator risk level. In this criterion, a value of “−2” is provided to dry, “-1” to CA, “1” is assigned for flooded and “2” in case of MQL condition. In dry and CA condition the amount of heat generation is very high which results in increase temperature of machined product and increases the operator risk level due to the exposure to high energy component. In the same time, in case of flooded condition the operator risk factor decreases due to control of temperature at the cutting zone. However, the maximum effective cooling is observed in MQL condition eligible to obtain score of “2”. During hard machining under dry and compressed air (CA) cooled conditions (i.e. cutting without coolant) provides obvious cost benefits. Therefore, the score of “2” is provided to the coolant cost for both dry and compressed air conditions, whereas a weightage of “−2” is given to flooded coolant as excessive amount of coolant is used in this case. In case of MQL, very little amount of coolant with compressed air is used in MQL condition, so it is assigned with “1” value. For factors both surface roughness and cutting temperature, “-2’ is provided to dry, “-1” is provided to CA, “1″ is given to flooded and “−2″ is assigned to MQL condition. In this process, the surface quality obtained in MQL process is superior than other cooling methods due to considerable control of cutting temperature is arrested in MQL condition. Concerning part cleaning, the score of “-2″ is allotted to dry condition, “2″ is provided to MQL condition and “1″ is assigned to both CA and flooded condition. The cost of part cleaning is more in dry condition as it is not using any kind of cutting fluid. In case of CA and flooded condition, due to the usages of compressed air and coolant, it flushes out the debris from the cutting zone and also clean the part. Moreover, due to the usage of cutting fluid with high speed compressed

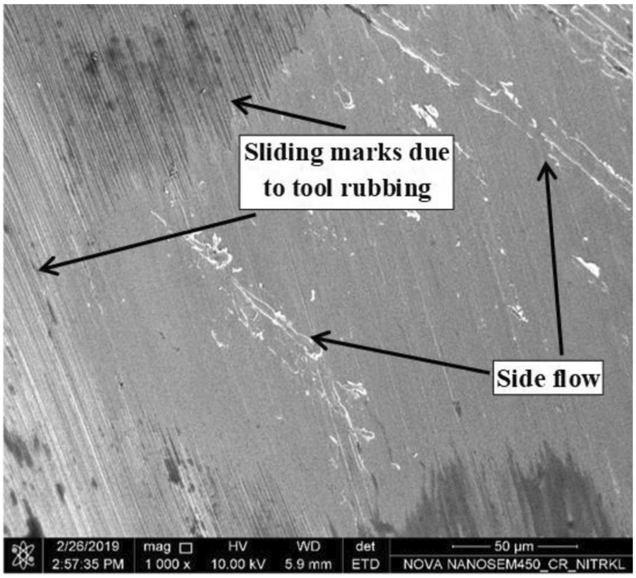


Fig. 25 Poor surface finish due to sliding marks

Table 6 Pugh matrix comparison for the cooling techniques

Sustainability assessment factors	Weightages			
	Dry	Compressed air	Flooded	MQL
Environmental effect	2	2	−2	-1
Worker safety	−2	-1	1	2
Coolant cost	2	2	−2	1
Surface roughness	-2	−1	1	2
Cutting temperature	-2	-1	1	2
Part cleaning	-2	1	1	2
Coolant recycling and disposal	2	2	-2	1
Noise level	-2	-1	1	2
Total +	6	7	5	12
Total -	−10	−4	−6	−1
Score	−4	3	−1	11

air in MQL condition, it effectively cleaned the machined part in comparison to pre-cited three cooling strategies. Hence, no post part cleaning is required in MQL condition. Regarding, coolant recycling and disposal a score "2″ is given to both dry and CA condition, as no cutting fluids are used in both the cases while, "-2″ is provided to flooded condition, as the cost of the coolant used was very high, also it required repeated cleaning and filtering which adds extra cost. In addition, disposal of used coolant also should follow some special procedure to minimize it harmful effect. However, a score of "1″ is provided to MQL, as it uses a very little (i.e. almost no) amount of coolant. Considering the noise level, the score of "-2″ and "−1″ is provided to dry and CA condition, respectively as high noise is produced in both the cases during the operation. In the contrary, a weightage of "1″ is provided to flooded and "2″ in case of MQL condition as the noise level decrease due to the usage of cutting fluid which results in lowering the cutting force and improved the tribological properties of coolant.

After calculation, the MQL acquired the maximum score of "11", followed by CA (3), then to flooded (−1), and last by dry condition (−4), which is reflected in Kiviat diagram, as shown in Fig. 26. In brief, machining with MQL condition is practically viable in terms of sustainability providing better economic and socio-technological benefits. However, to make such a decision, further investigation is required.

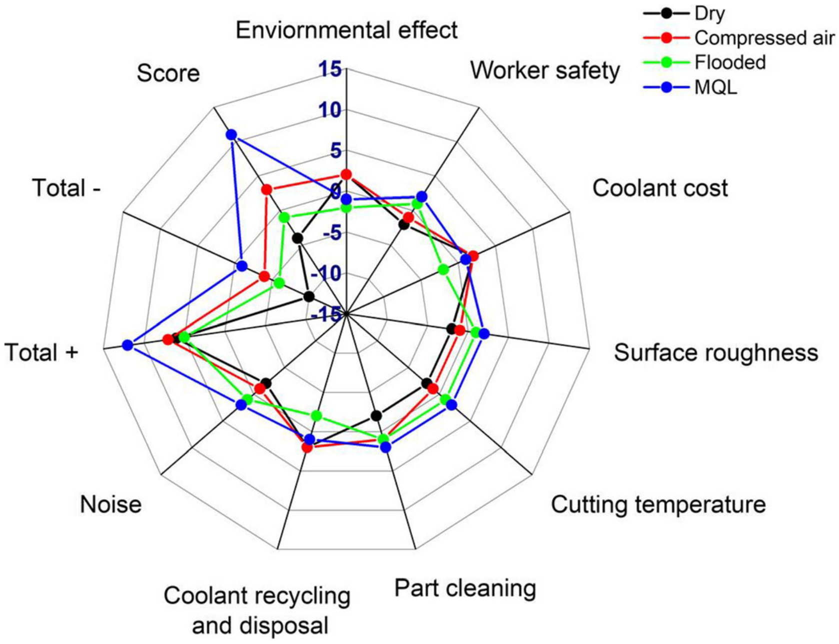


Fig. 26 Pugh matrix associated with Kiviat diagram for sustainability assessment

4 Conclusions

The paper presented the evaluation of the performances of the various machining environments (dry, compressed-air cooled, conventional wet, and MQL technique) applied in finish turning of austenitic stainless steel Nitronic 60 with new-generation SiAlON ceramic tool in terms of surface roughness, cutting force, cutting temperature, and tool wear. Additionally, comparative analysis was performed for sustainability assessment of machining process under various cooling-lubrication conditions. The following conclusions can be drawn from the present work:

- In comparison of among all four cooling-lubrication conditions, machining with MQL technique have shown an excellent performance in terms of (i) improved machined surface morphology as well as finish, (ii) reduced cutting forces, (iii) minimum cutting temperature, and (iv) lower tool (flank and crater) wear.
- When machining with high feed, machinability of difficult-to cut Nitronic 60 is reduced due to existence of intense cutting temperature as well as exorbitant cutting force, tool wear, and surface roughness. At high cutting speed exhibits: (i) unreasonable rise of cutting temperature and tool wear because of rubbing effect between tool-chip and tool-work interfaces, (iii) improved surface finish as well as lower value of tool force which are beneficial towards easier machining due to thermal softening of work material.
- Burr formation on the saw-tooth chip surface and friction greatly influenced notch wear on the tool flank face due to improper cooling and lack of lubrication in dry, wet and compressed air-cooled machining environments in comparison to MQL. SEM micrographs indicated that main patterns of surface defects included feed marks, adhered material particle, debris, side flows, tearing surface, surface plucking, etc.
- The application of ecofriendly radiator coolant in the form of pressurized coolant jet is implementable and preferable over dry as well as flooded machining to attain lower power consumption and longer tool life; this is attributed to the sufficient cooling and lubrication effects to reduce the friction at tool–workpiece contact point created by MQL.
- This study highlights that the application of minimum quantity lubrication-cooling technique in machining allows for obtaining a sustainable production in industrial application from techno-economical as well as ecological point of views. In brief, sustainable assessment approach reported that machining with MQL condition is practically viable in terms of reduced environmental impact, better operator safety, minimum coolant cost, excellent part cleaning, coolant recycling and disposal, lower noise level, improved surface finish, and controlled cutting temperature.
- From extensive experimental investigation, new-generation SiAlON ceramic tool can be effectively and efficiently used through machining of austenitic stainless steel Nitronic 60 under environmentally conscious minimum quantity lubrication surrounding that is most acceptable in industrial application and considered as environmentally and ecologically effective machining.
- To substitute of costlier CBN and PCBN tools, SiAlON ceramic tools can be preferred to bring high levels of productivity for the shaft making industry in finish turning operations of anti-galling and wear resistant austenitic stainless steel, especially ceramic tool having excellent wear resistance.
- This work provides flexibility to the decision maker(s) to select the appropriate cooling-lubrication strategy based on desired objectives and targets, whether these targets are focused on machining performance, sustainability effectiveness, or both.

In terms of future work, this study can be extended to include the application of other different cooling-lubrication (C/L) methods like, spray impingement cooling, nanofluid assisted MQL, and cryogenic cooling to compare the effectiveness of different C/L approaches towards machinability improvement. Moreover, the comprehensive study on chip formation and morphological analysis of chips will be thoroughly discussed in the future to physically understand the machinability performance of Nitronic 60 under using these C/L techniques. Attempt on modeling, then optimization of machining performance characteristics is scope of future work for machinability improvement and for comprehensive understanding the selection of appropriate cooling techniques as well as cutting conditions.

Nomenclature Symbol Description.
v Cutting speed.
f Feed rate.
d Depth of cut.
R_a Arithmetical mean roughness value.
F_c Principal cutting force.
VB Flank wear.
MRR Material removal rate.
CRC Chip reduction coefficient.
C/L Cooling/Lubrication.
SL Solid lubricant.
CA Compressed air.
MQL Minimum quantity lubrication.
NFMQL Nano fluid based minimum quantity lubrication.
NDL Near dry lubrication.
NDM Near dry machining.
HPC High pressure coolant.
BUE Built-up-edge.
AISI American iron and steel institute.
SS Stainless steel.
HSLA High strength low alloy.

CBN Cubic boron nitride.
PCBN Polycrystalline cubic boron nitride.
WC Tungsten carbide.
PVD Physical vapor deposition.
CVD Chemical vapor deposition.
MTCVD Medium temperature chemical vapor deposition.
HiPIMS High-power impulse magnetron sputtering.
SEM Scanning electron microscopy.
EDS Energy-dispersive X-ray spectroscopy.
J-C Johnson-Cook.

References

1. Liew PJ, Shaaroni A, Sidik NAC, Yan J (2017) An overview of current status of cutting fluids and cooling techniques of turning hard steel. Int J Heat Mass Transf 114:380–394
2. Chinchanikar S, Choudhury SK (2014) Hard turning using HiPIMS-coated carbide tools: Wear behavior under dry and minimum quantity lubrication (MQL). Measurement 55:536–548
3. Saini A, Dhiman S, Sharma R, Setia S (2014) Experimental estimation and optimization of process parameters under minimum quantity lubrication and dry turning of AISI 4340 with different carbide inserts. J Mech Sci Technol 28(6):2307–2318
4. Elmunafi MHS, Mohd Yusof N, Kurniawan D (2015) Effect of cutting speed and feed in turning hardened stainless steel using coated carbide cutting tool under minimum quantity lubrication using castor oil. Advances in Mechanical Engineering 7(8):1–7
5. Sarıkaya M, Güllü A (2015) Multi-response optimization of minimum quantity lubrication parameters using Taguchi-based grey relational analysis in turning of difficult-to-cut alloy Haynes 25. J Clean Prod 91:347–357
6. Kamruzzaman M, Rahman SS, Ashraf MZI, Dhar NR (2016) Modeling of chip–tool interface temperature using response surface methodology and artificial neural network in HPC-assisted turning and tool life investigation. Int J Adv Manuf Technol 90(5–8):1547–1568
7. Tamang SK, Chandrasekaran M, Sahoo AK (2018) Sustainable machining: an experimental investigation and optimization of machining Inconel 825 with dry and MQL approach. J Braz Soc Mech Sci Eng 40(8):374
8. Mia M, Gupta MK, Singh G, Królczyk G, Pimenov DY (2018) An approach to cleaner production for machining hardened steel using different cooling-lubrication conditions. J Clean Prod 187:1069–1081
9. Ukamanal M, Mishra PC, Sahoo AK (2019) Effects of spray cooling process parameters on machining performance AISI 316 steel: a novel experimental technique. Experimental Techniques J Expt Tech 44:19–36. https://doi.org/10.1007/s40799-019-00334-y
10. Gupta MK, Mia M, Pruncu CI (2019) Parametric optimization and process capability analysis for machining of nickel-based superalloy. Int J Adv Manuf Technol 102(9–12):3995–4009
11. Abbas AT, Benyahia F, El Rayes MM, Pruncu C, Taha MA, Hegab H (2019) Towards optimization of machining performance and sustainability aspects when turning AISI 1045 steel under different cooling and lubrication strategies. Materials 12:1–17
12. Naigade DM, Patil DH, Sadaiah M (2013) Some investigations in hard turning of AISI 4340 alloy steel in different cutting environments by CBN insert. Int J Mach Mach Mater 14(2):165–193
13. Sahu SK, Mishra PC, Orra K, Sahoo AK (2014) Performance assessment in hard turning of AISI 1015 steel under spray impingement cooling and dry environment. Proc Inst Mech Eng B J Eng Manuf 229(2):251–265
14. Dureja JS, Singh R, Singh T, Singh P, Dogra M, Bhatti MS (2015) Performance evaluation of coated carbide tool in machining of stainless steel (AISI 202) under minimum quantity lubrication (MQL). International Journal of Precision Engineering and Manufacturing-Green Technology 2(2):123–129
15. Makhesana MA, Patel KM (2016) Investigation to study the applicability of solid lubricants in machining for clean and green manufacturing. Industrial Lubrication and Tribology 68(5):591–596
16. Mia M, Khan MA, Dhar NR (2016) Performance prediction of high-pressure coolant assisted turning of Ti-6Al-4V. Int J Adv Manuf Technol 90(5–8):1433–1445
17. Panday G, Ashraf MZI, Ibn Muneer K, Hossain KS, Ashik MFK, Kamruzzaman M (2018) Assessing near-dry lubrication (35 ml/h) performance in hard turning process of hardened (48 HRC) AISI 1060 carbon steel. Int J Adv Manuf Technol 99(5–8):2045–2057
18. Das SR, Dhupal D, Kumar A (2015) Experimental investigation into machinability of hardened AISI 4140 steel using TiN coated ceramic tool. Measurement 62:108–126
19. Kumar R, Sahoo AK, Mishra PC, Das RK (2018) Comparative investigation towards machinability improvement in hard turning using coated and uncoated carbide inserts: part I experimental investigation. Advances in Manufacturing 6(1):52–70
20. Gupta M, Pruncu C, Mia M, Singh G, Singh S, Prakash C et al (2018) Machinability investigations of Inconel-800 super alloy under sustainable cooling conditions. Materials 11(11):1–13
21. Das A, Tirkey N, Patel SK, Das SR, Biswal BB (2019) A comparison of machinability in hard turning of EN-24 alloy steel under mist cooled and dry cutting environments with a coated cermet tool. J Fail Anal Prev 19(1):115–130
22. Das A, Das SR, Patel SK, Biswal BB (2019) Effect of MQL and nanofluid on the machinability aspects of hardened alloy steel. Mach Sci Technol. https://doi.org/10.1080/10910344.2019.1669167
23. Panda A, Das SR, Dhupal D (2019) Machinability investigation of HSLA steel in hard turning with coated ceramic tool: assessment, Modelling. Optimization and Economic Aspects Journal of Adv Manuf Systems. https://doi.org/10.1142/s0219686719500331
24. Kumar R, Sahoo AK, Mishra PC, Das RK (2019) Measurement and machinability study under environmentally conscious spray impingement cooling assisted machining. Measurement 135:913–927
25. Ning J, Nguyen V, Liang SY (2018) Analytical modeling of machining forces of ultra-fine-grained titanium. Int J Adv Manuf Technol 101(1–4):627–636
26. Ning J, Liang S (2018) Prediction of temperature distribution in orthogonal machining based on the mechanics of the cutting process using a constitutive model. Journal of Manufacturing and Materials Processing 2(2):37
27. Ning J, Liang S (2019) Predictive modeling of machining temperatures with force–temperature correlation using cutting mechanics and constitutive relation. Materials 12(2):284
28. Ning J, Liang SY (2019) A comparative study of analytical thermal models to predict the orthogonal cutting temperature of AISI 1045 steel. Int J Adv Manuf Technol 102:3109–3119
29. Ning J, Nguyen V, Huang Y, Hartwig KT, Liang SY (2019) Constitutive modeling of ultra-fine-grained titanium flow stress for machining temperature prediction. Bio-Design and Manufacturing 2(3):153–160
30. Zheng G, Zhao J, Gao Z, Cao Q (2011) Cutting performance and wear mechanisms of Sialon–Si3N4 graded nano-composite ceramic cutting tools. Int J Adv Manuf Technol 58(1–4):19–28
31. Ceramics for High-Temp Alloy Machining. https://www.kennametal.com/Catalogs-Literature/Metalworking/SuperAlloys_material_machining_guide_Aerospace
32. Vagnorius Z, Sørby K (2010) Effect of high-pressure cooling on life of SiAlON tools in machining of Inconel 718. Int J Adv Manuf Technol 54(1–4):83–92

33. Dogra M, Sharma VS, Sachdeva A, Suri NM, Dureja JS (2010) Tool wear, chip formation and workpiece surface issues in CBN hard turning: a review. Int J Precis Eng Manuf 11(2):341–358
34. König W, Klinger M, Link R (1990) Machining hard materials with geometrically defined cutting edges — field of applications and limitations. CIRP Ann 39(1):61–64
35. Sobiyi K, Sigalas I (2015) Chip formation characterisation and tem investigation of worn PcBN tool during hard turning. Mach Sci Technol 19(3):479–498
36. Yıldırım ÇV, Kıvak T, Sarıkaya M, Erzincanlı F (2017) Determination of MQL parameters contributing to sustainable machining in the milling of Nickel-Base Superalloy Waspaloy. Arab J Sci Eng 42(11):4667–4681
37. Anand A, Behera AK, Das SR (2019) An overview on economic machining of hardened steels by hard turning and its process variables. Manufacturing Review 6(4):1–9
38. Hegab H, Umer U, Soliman M, Kishawy HA (2018) Effects of nano-cutting fluids on tool performance and chip morphology during machining Inconel 718. Int J Adv Manuf Technol 96(9–12): 3449–3458
39. Keblouti O, Boulanouar L, Azizi MA, Yallese MA (2017) Effects of coating material and cutting parameters on the surface roughness and cutting forces in dry turning of AISI 52100 steel. Struct Eng Mech 61(4):519–526
40. Shaw MC (2005) Metal cutting principles2nd edn. Oxford University Press, New York
41. Mashinini PM, Soni H, Gupta K (2019) Investigation on dry machining of stainless steel 316 using textured tungsten carbide tools. Materials Research Express 7(1):016502