Machining of Austenitic Stainless Steel Under Various Cooling-Lubrication Strategies

Smita Padhan, Ajay Kumar Behera, and Sudhansu Ranjan Das

Abstract This work highlights the performance analysis of four distinct cooling-lubrication techniques (dry, flood, minimum quantity lubricant MQL and compressed-air) in turning Nitronic 60 by using new generation SiAlON ceramic inserts. Several machinability parameters such as cutting force, cutting temperature, cutting tool wear, surface finish and cost estimation were analyzed for machining performance evaluation. It was observed that machining under MQL condition exhibit beneficial effects as compared to other three pre cited cooling and lubrication condition as the cutting fluid is applied in spray jet form to the cutting zone. Result shows that the tool life in machining under MQL are 138, 72 and 11% greater than dry, compressed air, flooded condition, respectively. The use of SiAlON ceramic tool results in more economically feasible under MQL environment as the total machining cost per component is lower (Rs. 19.79) in comparison to dry (Rs. 26.81), compressed air (Rs. 23.4), flooded (Rs. 21.76) machining conditions.

Keywords Machinability · Cost analysis · Cutting environment · SiAlON ceramic · Nitronic 60

1 Introduction

In present day, nickel-based alloys are commonly employed for various industrial applications because of its unique properties like weldability, formability, capability to retain its strength and toughssness at elevated temperature, excellent resistance to creep, thermal and corrosion. Because of its outstanding physical and chemical properties, the use of nickel-based alloy is not only bound to aerospace industry but it

S. Padhan · S. R. Das (✉)
Department of Production Engineering, Veer Surendra Sai University of Technology, Burla 768018, India
e-mail: das.sudhansu83@gmail.com

A. K. Behera
Department of Mechanical Engineering, Siksha 'O' Anusandhan University, Bhubaneswar 751030, India

P. Pradhan et al. (eds.), *Recent Advances in Mechanical Engineering*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-16-9057-0_46

also extensively used in nuclear power plant, oil and gas power industries, architecture building and construction, transport, food processing equipment, in various consumer products and medical applications.

Despite various advanced methods, machining is still considered to be one of the commonly used processes as the manufacturer can easily achieve the desired structural and the functional features on the component. However, the manufacturing engineer faces big challenges to machine nickel-based alloys as very high temperature and stress are developed during machining resulting work hardening of workpiece which primarily impacts on the tool life and surface quality of machined component. If the selection of cutting parameters and their ranges is not chosen properly with reference to the selected tool and work material combination, then it can lead to the degradation of workpiece quality and failure of the cutting tool by exceeding its tolerance limits. Therefore, to minimize the above pre-cited issues the use of an effective C/L environment is very essential which will be valuable from technological, economic and ecological prospective. The use of cutting fluids in machining process by using different C/L strategies remarkably increase the efficiency of the cutting operation by minimizing friction, controlling heat generation at the machining zone, improving chip removal rate and preventing corrosion. The cutting fluids effectively extract heat from machining area by continuously flowing through the cutting zone. It can also provide lubrication effect by forming a thin layer of oil film on cutting interface depending upon adhesive and cohesive nature of cutting fluid. Many researchers have been worked on different C/L strategies [1–4] to enhance the cutting performance [5, 6] and machinability [7, 8] of different hard-to-cut and difficult-to-cut workpiece materials during turning operation (EN-24, EN-31,42CrMo4, 17CrNiMo6, Haynes-25, Ti6Al4V, Inconel 825, 800, 718, AISI 202, AISI 316, AISI 420, AISI 1015, AISI 4140, AISI 4340, AISI 1045, AISI 1060, AISI 52,100, AISI D2). Based on considering previous research contribution, the primary purpose of the present study is (i) to evaluate cutting efficiency of modern generation SiAlON ceramic insert, (ii) to explore a comparative investigation toward machinability enhancement by using different cooling lubrication methods (i.e. MQL, flooded, compressed air-cooled, and dry) and (iii) to evaluate the overall machining cost per part during turning under various C/L environments.

2 Experimental Setup and Procedure

To achieve the objectives, the experiments were conducted by turning a cylindrical bar of Nitronic 60 austenitic stainless steel (diameter: 50 mm, length: 500 mm) as work material. The turning experiments were conducted on an HMT made high accuracy robust lathe having maximal power rating of 11 kW and highest speed limited to 2050 rpm. The cutting tool applied in the experiments is a KYS30 grade new generation SiAlON ceramic insert manufactured by Kenametal in the form of SNMG 120,412. During the turning operation, the ceramic insert is rigidly clamped to an ISO standard toolholder having description of PSBNR2020K12. Principal cutting force (Fc) is measured with the 9257B piezoelectric dynamometer manufactured by Kistler. A roughness tester (model: Surftest SJ-210, manufactured by Mitutoyo) is used to measure the roughness value (Ra) of machined component after each experimental run. A high-resolution digital imaging microscope (model: Axiotech 100HD-3D) manufactured by Carl Zeiss was employed to measure tool wears on rake as well as flank surface of the tool insert after completion of each experimental trial. FLUKE made $Ti3_2$ infrared thermal imaging camera was employed to monitor the cutting temperature at the interface of workpiece and cutting edge of tool. A JSM-6084LV model scanning electron microscope (make: JOEL) was used to perform microstructural analysis of machined surface and worn-out tool after the turning experiment. Figure 1 depicts the experimental setup and work methodology followed by the present machinability investigation. The output responses considered in this study are surface quality, tool wear on both flank and rake face of insert, principal cutting force and machining zone temperature. The details of all input cutting factors and cutting condition taken in this study were summarized in Table 1.

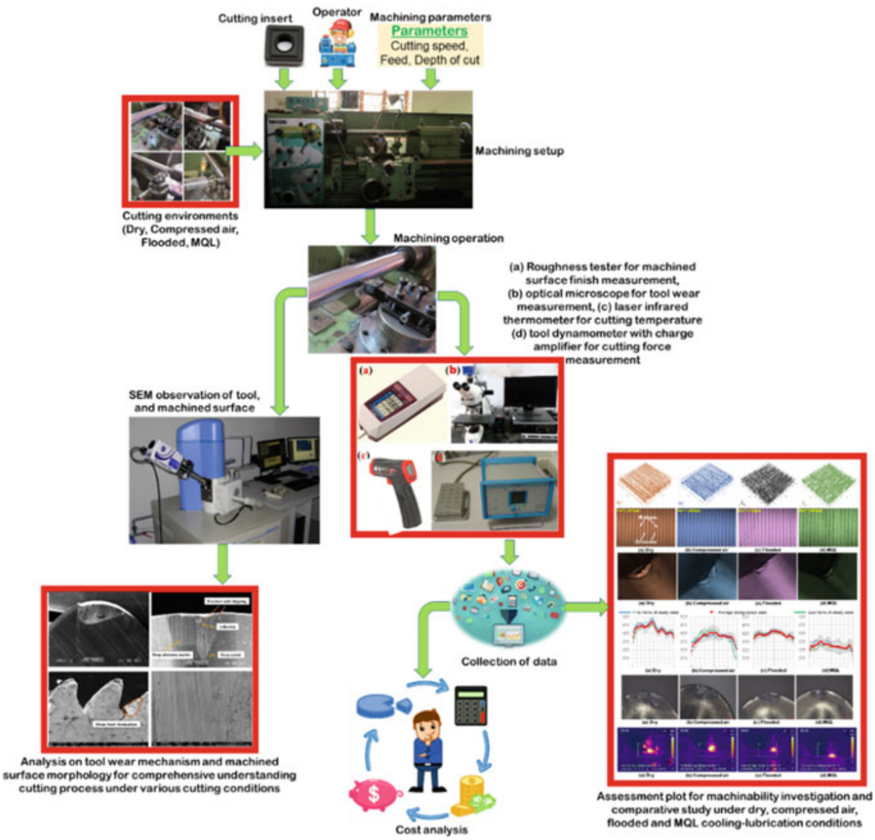

Fig. 1 Schematic representation of proposed methodology and experimental setup layout

Table 1 Details of cutting process variable and their levels

Input parameters	Range
Axial seed (mm/rev)	0.12, 0.16, 0.20, 0.24
Machining speed (m/min)	51,67,87,111
Depth of cut (mm)	0.4
Cutting duration (s)	120
C/L strategy	MQL, flooded, compressed air-cooled, and dry

3 Discussion of Results

The optical images of carter wear under different machining environments (dry, compressed air, flooded, MQL) are shown in Fig. 2a. In dry as well as compressed air-cooled cutting conditions, due to the weak heat transfer capability of cooling medium, large amount of heat is generated at the interface of tool and workpiece, which is responsible for the development of thermal stress, which leads to the starting of cracking will on rake face followed by edge chipping. However, due to the surplus availability of coolant at the cutting zone in flooded cooling condition, large amount of heat was taken out from the cutting zone, so it effectively minimizes the carter wear by reducing the generation of thermal stress on the tool rake surface. For MQL condition, as cutting fluid is applied in jet form to the cutting zone at high pressure, it effectively extracted heat from the cutting zone and resulting decease in thermal stress build up in cutting tool. Thus, a very less chipping was observed on the tool insert in MQL condition compared to other C/L environment. Still some edge chipping was observed in MQL condition. Figure 2b shows flank wear on cutting insert in different C/L methods. Maximum flank wear was observed in dry cutting environment, whereas it was minimum in MQL cutting. Since, coolant is not applied in dry turning the heat generated during cutting is accumulated at cutting region causing rapid increase in cutting temperature. This high temperature promoted the formation of notch due to high thermal stress and adhesion of melted chip to the flank surface of the tool. Due to improper lubrication, chipping and abrasion type of wear are also seen on the flank face of cutting tool. However, in provision for MQL condition, due to its effective C/L capacity, slight edge chipping, negligible adhered material, compact notch, and very smooth abrasion marks were noticed, whereas compressed air-cooled condition gave better result in comparison to dry cutting condition. Figure 2c depicts IR thermography of cutting zone temperature in different cooling-lubrication methods using IR thermal imaging camera. Moreover, Fig. 2d shows the measurement signal images of the cutting temperature under the influence of various C/L environments. Maximum temperature was observed in dry cutting environment, whereas it was minimum in MQL condition. The use of coolant reduces the cutting temperature by providing highly effective heat extracting medium as well as lubrication. In addition, the reason of less heat generation in MQL condition is that, here the friction in between the tool-chip is deceased as the contact length

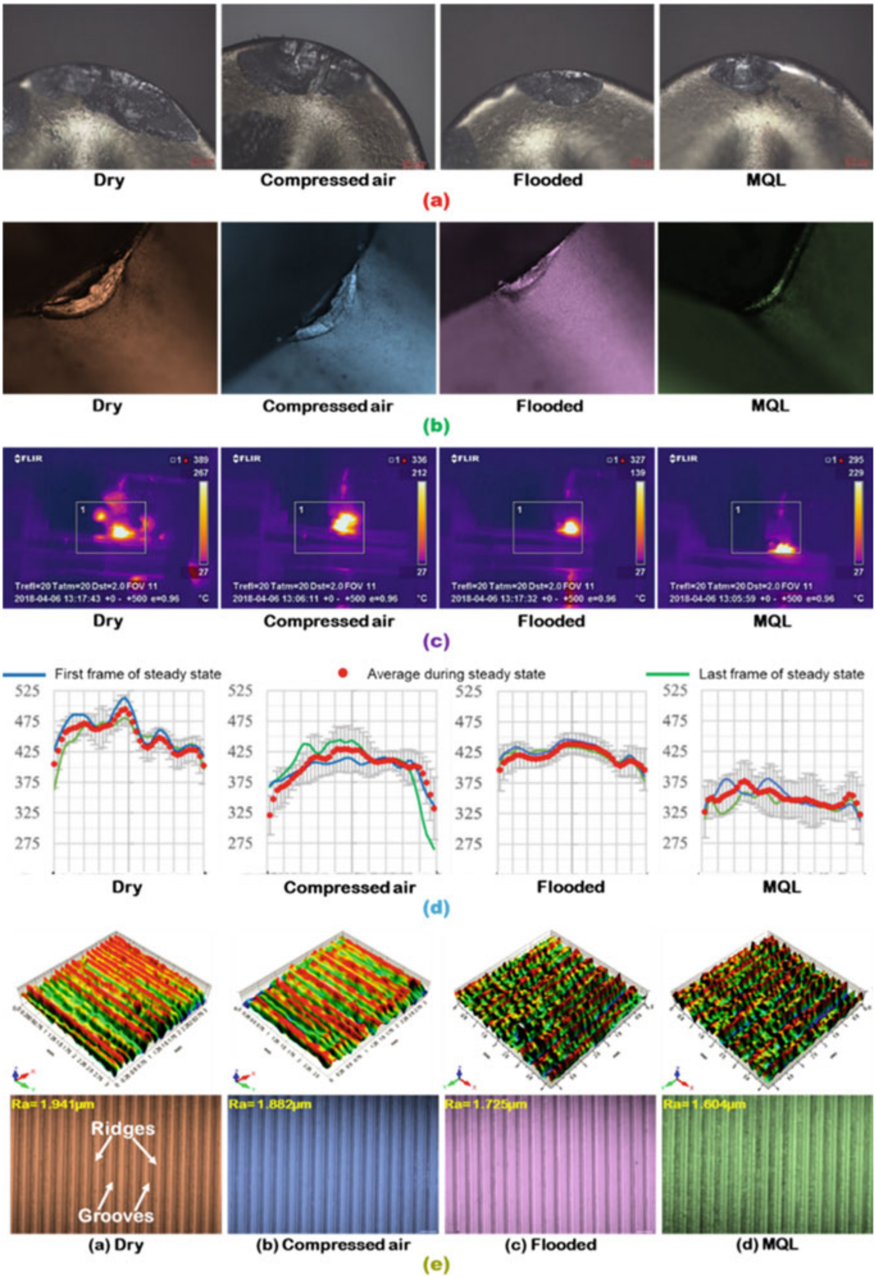

Fig. 2 Machinability study under various turning environments at $v = 111$ m/min, $f = 0.24$ mm/rev, $d = 0.4$ mm: **a** Crater wear, **b** Flank wear, **c** & **d** Cutting temperature, **e** Surface finish

between chip and tool is reduced. Figure 2e depicts the optical images and 3D images of machined surfaces in precited turning environments. Out of the four precited cutting conditions, the surface topography of machined surface (3D image profile) clearly reflects that turning with MQL presents a lower peak compared to other machining environments. Also, Fig. 2e shows reasonably low feed marks and feed mark area expansion to ridges under MQL. As the absence of cutting fluid in dry turning, high friction is generated at tool- work interface resulting wear at the cutting edge followed by increasing in cutting force. This increase in the principal cutting force consequently enhance the roughness value of the machined surface. In flooded condition, due to the presence of abundant cutting fluid which provide desired cooling and lubrication effect, which leads to reduction in cutting edge wear followed by improving surface quality. In case of MQL turning, as cutting fluid is supplied in spray form, due to aerosolization of cutting fluid effective cooling is obtained at the cutting zone. Thus, it subsequently protects the tool from the thermal stress and able to uphold the effectiveness of the cutting insert. In addition, cutting forces also increase comparatively less to other cooling methods.

By taking into consideration of control criterion of flank wear (i.e., VB till 0.3 mm), one more experiment was performed for each precited C/L condition by setting cutting speed and feed at their higher limit (i.e., $v = 111$ m/min and $f = 0.24$ mm/rev) and doc at 0.4 mm for estimating tool life of SiAlON ceramic cutting insert. Effective cooling-lubrication capability by MQL technique results in improvement of tool life. Machining under above four precited C/L conditions experience the tool life of 34, 47, 73 and 81 min, respectively. These obtained results show that the tool life in turning in MQL are 138, 72 and 11% greater than dry, compressed air, flooded condition, respectively. To study the economic feasibility, Gilbert's approach was employed to estimate overall machining cost per component considering both direct and indirect cost associated with machining, as shown in Table 2. Results

Table 2 Cost analysis in turning Nitronic 60 with SiAlON ceramic toolunder various environments

Sl. no	Type of costs	Dry	Compressed air	Flooded	MQL
1	Machine and labor cost (×) per min	Rs. 5	Rs.5.17	Rs. 6	Rs. 5.42
2	Cutting cost per component (xT_m)	Rs. 12.75	Rs. 13.18	Rs. 15.3	Rs. 13.82
3	Tool changing cost per component [xT_d (T_m/T)]	Rs. 1.87	Rs. 1.4	Rs. 1.05	Rs. 0.85
4	Cost of each tool	Rs. 650	Rs. 650	Rs. 650	Rs. 650
5	Average cost of each cutting tool edge (y)	Rs. 162.5	Rs. 162.5	Rs. 162.5	Rs. 162.5
6	Tooling cost per piece [y (T_m/T)]	Rs. 12.19	Rs. 8.82	Rs. 5.68	Rs. 5.12
7	Overall cutting cost per piece, (2 + 3 + 6)	Rs. 26.81	Rs. 23.4	Rs. 21.76	Rs. 19.79

obtained from cost analysis reveals that the utilization of SiAlON ceramic tool is more economically feasible under MQL environment as the overall machining cost per component is lower (Rs. 19.79) as compared to dry (Rs. 26.81), compressed air (Rs. 23.4), flooded (Rs. 21.76) machining conditions. Thus, cost saving can be attained when using SiAlON ceramic tool in MQL condition.

4 Conclusions

Machining with MQL relatively performed well as compared to above three precited C/L condition and effectively removed heat and dewberries from the cutting zone and provided better cooling and lubrication effect. Implementation of MQL technique results in (i) minimizing cutting force by decreasing thermal stress. (ii) improve surface quality by providing better cooling and lubrication (iii) decrease cutting temperature by effectively removing heat from cutting zone and (iv) lower tool wear rate by decreasing thermal stress. During the investigation, the tool life of 81 min is recorded for MQL condition, whereas it was found to be 34, 47 and 73 in case of dry cutting, compressed air-cooled and flooded condition. Result shows that the tool life in machining under MQL are 138, 72 and 11% greater than dry, compressed air, flooded condition, respectively. The use of SiAlON ceramic tool results in more economically feasible under MQL environment as the total machining cost per component is lower (Rs. 19.79) in comparison to dry (Rs. 26.81), compressed air (Rs. 23.4), flooded (Rs. 21.76) machining conditions.

References

1. 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):1–13
2. 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
3. Ukamanal M, Mishra PC, Sahoo AK (2020) Effects of spray cooling process parameters on machining performance AISI 316 steel: a novel experimental technique. Exp Tech 44(1):19–36
4. Gupta MK, Mia M, Pruncu CI, Kapłonek W, Nadolny K, Patra K, Sarikaya M, Sharma VS (2019) Parametric optimization and process capability analysis for machining of nickel-based superalloy. Int J Adv Manuf Technol 102(9–12):3995–4009
5. Mia M, Khan MA, Dhar NR (2017) Performance prediction of high-pressure coolant assisted turning of Ti-6Al-4V. Int J Adv Manuf Technol 90(5–8):1433–1445
6. 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

7. 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
8. Panda A, Das SR, Dhupal D (2019) Machinability study of HSLA steel in hard turning with coated ceramic tool: assessment, modeling, optimization and economic aspect. J Adv Manuf Syst 18(4):625–655