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Hole-Making in Nickel-Based Superalloys using the Expanding Jet of CO_2 and Through-the-Tool Micro-Lubrication

Asif Iqbal, Muhammad Izzuddin Hj Sabaruddin and Malik Muhammad Nauman
Faculty of Integrated Technologies, Universiti Brunei Darussalam
Jalan Tungku Link, Gadong BE 1410, Brunei Darussalam
asif.iqbal@ubd.edu.bn; izzuddin.sabaruddin@gmail.com; malik.nauman@ubd.edu.bn

Jannis Saelzer
Institute of Machining Technology (ISF), Technische Universität Dortmund
Baroper Str. 303, 44227 Dortmund, Germany
jannis.saelzer@tu-dortmund.de

Abstract

Nickel-based superalloys are highly difficult-to-cut materials due to their high strength and retention at elevated temperatures, high toughness, extreme strain hardening, adhesivity with most tool materials, and relatively low thermal conductivities. Drilling these materials poses an additional challenge because of the slenderness of the tool and the inaccessibility of cutting fluids to the cutting zones. This work assesses the effectiveness of (a) providing a throttle cryogenic coolant (an expanding jet of compressed CO_2) onto the cutting lips through the body of the tool, (b) replacing the coolant with through-the-tool micro-lubrication, and (c) combining (b) with an external supply of the throttle cryogenic coolant. These three approaches are tested in the hole-making of the following nickel-based superalloys: Inconel 718, Incoloy 825, and Waspaloy. The performance measures evaluated include tool wear, thrust force, cutting torque, hole surface roughness, and temperature profile of the work face parallel to the hole axis. The first approach had a catastrophic impact on the tool's structural integrity, causing it to rupture near the cutting lips due to embrittlement resulting from excessive cooling in that area, combined with intense dynamic loading. In contrast, a through-the-tool supply of micro-lubrication yielded highly favorable results concerning the measured responses, especially when paired with an external supply of the cryogenic coolant. The hybrid lubri-cooling approach, combining the external and internal supplies of compressed CO_2 and micro-lubrication, respectively, demonstrated the best performance by reducing tool wear, stabilizing thrust force and cutting torque, and improving surface quality, particularly at high levels of cutting speed.

Keywords
Inconel 718, Cryogenic Cooling, Incoloy 825, Drilling, Waspaloy

1. Introduction
Nickel-based superalloys are widely used in applications requiring high strength, durability, and creep resistance, such as nuclear reactors, gas turbines, aerospace, and chemical processing, due to their remarkable strength, corrosion resistance, and thermal stability (Ezugwu 2005). These properties allow the materials to withstand harsh operating environments, including elevated temperatures and corrosive substances, which make them invaluable in high-stakes industries (Thakur et al. 2009). However, the same properties contribute to the machining difficulties associated with these alloys. High flow strengths marred by extreme work hardening, chemical adhesivity with tool materials, high toughness, and low thermal conductivities, leading to accumulation of process heat near the cutting edges, resulting in

substantially high temperatures, which quickly degrade the cutting tools and necessitate frequent replacements (Ezugwu 2005). Additionally, the tendency to form a built-up edge during machining compromises tool performance and work surface quality (Guo et al. 2018). The machining complications are further pronounced when drilling these superalloys because of the slenderness of the drilling tool, subject to an enhanced chip load, and the inaccessibility of the cutting fluids to the cutting lips.

1.1 Objectives

This work aims to introduce a novel lubrication-cooling approach for drilling nickel-based superalloys. This method intends to effectively dissipate process heat and enhance tribological conditions in the cutting zones. Doing so seeks to reduce tool damage and increase productivity by improving the material removal rate. The objective is to compare the effects of introducing a cryogenic coolant directly through the tool against supplying it from an external source, with and without the parallel addition of micro-lubrication. This comparison focuses on drilling performance measures, such as tool damage, cutting torque, thrust force, surface roughness, and the work temperature profile.

2. Literature Review

The machining of nickel-based superalloys presents significant challenges due to their unique properties, including high-temperature resistance and low thermal conductivity (Elshwain and Redzuan 2013; Rajguru and Vasudevan, 2018). Coolants and lubricants are essential to the machining process to improve productivity and tool life (Ramanujam et al. 2018). Recent research has focused on developing advanced cooling and lubrication techniques to enhance machining performance, such as cryogenic cooling, minimum quantity lubrication (MQL), and high-pressure lubri-coolant supply (Jemielniak 2021). These methods enhance tool life, reduce cutting temperatures, and improve surface finish (Elshwain and Redzuan 2013). The choice of cutting approach and cooling conditions significantly influences the machining process, affecting tool wear, surface quality, and overall performance (Panigrahi et al. 2019). Researchers have compared various cooling environments to optimize machining parameters for different superalloy grades, including cryogenic, MQL, and dry conditions.

Conventional flood cooling methods effectively reduce cutting zone temperatures but raise environmental and safety concerns due to the overflow of cutting fluids (Ray 2014). As an alternative, MQL and cryogenic cooling methods have gained traction as more sustainable and effective cooling strategies (Rahim et al. 2015). In MQL, applying a small amount of fluid significantly reduces friction in the secondary and tertiary shear zones. It enhances machining conditions, especially when applied through the tool internally, which is beneficial in operations like drilling, tapping, and reaming (Osman et al. 2019). Cryogenic cooling, using coolants like liquid nitrogen (LN_2) and compressed carbon dioxide (CO_2), is also recognized for its ability to improve tool life under high-temperature machining conditions (Busch et al. 2016).

In recent studies, cryogenic methods have proven effective in maintaining low cutting temperatures and increasing tool durability during machining. For instance, LN_2 has shown superior cooling effects, but its very low temperature may lead to tool brittleness, while CO_2 provides a more balanced and sustainable cooling performance(Yildirim et al. 2020). Previous work involving throttle cryogenic cooling has shown benefits for sustainability in machining, particularly at higher cutting speeds (Iqbal et al. 2021). Hybrid cooling techniques are superior for achieving longer tool life and smoother surface finish when milling Inconel 718 (Sivadasan et al., 2020). The effectiveness of cooling methods varies depending on the specific alloy, manufacturing process, and machining conditions. Minimum quantity lubrication and cryogenic cooling show promise for improving surface finish in titanium alloy machining, while high-pressure cooling enhances chip breakability and tool life in titanium machining but yields mixed results for nickel alloys (Pimenov et al. 2024). Throttle cryogenic cooling using compressed CO_2, applied in continuous and pulsed modes, has shown promising results in milling nickel-based superalloys (Iqbal et al. 2024). The pulsed mode, especially when combined with micro-lubrication, outperformed continuous cooling regarding cutting forces and surface roughness (Iqbal et al. 2023).

This study introduces new methods of lubri-cooling by supplying a throttle cryogenic coolant through the tool and combining external cryogenic cooling with a parallel addition of the micro-lubrication provided through the tool. This lubri-cooling mechanism aims to improve the drilling process for hole-making in Incoloy 825, Waspaloy, and Inconel 718 by comparing different configurations of coolant applications—internal versus external—across multiple cutting speeds.

3. Data Collection

3.1 Control Parameters and Responses

The effects of the following three control parameters are investigated:

(1) Work material: The experiments test drilling on three nickel superalloys, Inconel 718, Incoloy 825, and Waspaloy.
(2) Lubri-cooling and the route of delivery. This parameter is tested at five levels: Dry, Through-the-tool/Internal CO_2 cooling (C-I), External CO_2 cooling (C-E), Through-the-tool/Internal micro-lubrication (L-I), and Hybrid lubri-cooling, i.e., external CO_2 + through-the-tool micro-lubrication (LC).
(3) Cutting Speed (v_c). This parameter is tested at various levels, ranging from 9 to 32 m/min.

A total of 24 experiments were conducted with all three materials. It is important to note that a formal Design of Experiment (DoE) could not be implemented due to the high risk of tool failure under the given conditions. In this study, the focus is on assessing the feasibility of the process rather than optimizing it. The following five key responses are measured and analyzed for each experimental run.

(1) The average width of the flank wear land; VB (μm)
(2) Thrust force (the force component in the direction of cutting feed); F (N)
(3) Drilling torque; τ (N-mm)
(4) Average arithmetic roughness of the holes' surface; Ra (μm)
(5) Temperature profile of the side wall of the workpiece; T_{max} (°C) is the maximum temperature recorded during the cutting of a hole.

3.2 Drilling Tools and Work Material

The study examines the responses of three nickel superalloys: Inconel 718, Incoloy 825, and Waspaloy, concerning the previously mentioned control parameters of cryogenic drilling. Inconel 718 is a commonly used high-strength, corrosion-resistant nickel-chromium alloy that is precipitation-hardened and contains substantial amounts of iron, molybdenum, niobium, and smaller amounts of titanium and aluminum. Its excellent strength, remarkable toughness, and significant work hardening contribute to its machining difficulties. In contrast, Incoloy 825 is a less widely recognized heat-treatable nickel-iron-chromium alloy. It possesses notable, though lesser, molybdenum, titanium, and copper proportions compared to Inconel 718. The primary distinction is that Incoloy 825 has a lower nickel content, resulting in a higher iron content that makes it marginally easier to machine. Waspaloy is another nickel-based superalloy with chemical composition and mechanical attributes similar to Inconel 718, more so than Incoloy 825. The workpieces are used in their annealed state. Tables 1 and 2 provide the three superalloys' chemical compositions and mechanical properties, respectively.

The drilling experiments utilize ceramic-coated (TiAlN) cemented tungsten carbide (WC) twist drills from Gühring, Inc. The drills have geometric dimensions of 8 mm in diameter, a 140° point angle, a 40 mm groove length, and a total length of 79 mm.

Table 1. Chemical composition of Inconel 718, Incoloy 825, and Waspaloy (in percentage)

	Ni	Cr	Fe	Mo	Cu	Ti	C	Mn	Co	Si	Al
Inconel 718	52	19	17	2.8	0.25	0.6	0.06	0.25	0.9	0.3	0.4
Incoloy 825	43	24	26	3.1	2	0.9	0.03	0.3	-	0.44	0.2
Waspaloy	54	19.5	2	4.25	0.5	3	0.07	1	13.5	0.75	1.4

Table 2. Mechanical properties of the three nickel-based superalloys

	Tensile Strength	Yield Strength	Elongation	Hardness	Thermal Conductivity
Inconel 718	703 MPa	340 MPa	39 %	22 HRc	11.1 W/m.K
Incoloy 825	1035 MPa	725 MPa	25 %	32 HRc	11.4 W/m.K
Waspaloy	888 MPa	443 MPa	49 %	24 HRc	11.3 W/m.K

3.3 Experimental Setup

All experiments were conducted using the Chiron FZ 12S Magnum vertical machining center, which can achieve a maximum rotational speed of 15,000 rpm and generate up to 8 kW of power. This machine is designed to accommodate HSK-63 tool holders. The drilling tools were secured in a Weldon tool holder with a consistent overhang length of 50 mm. The workpieces were saw-cut from a larger block and milled to 200 mm × 40 mm × 18 mm. The drilling tool was applied perpendicularly to the 200 mm × 18 mm face, with the feed directed along the 40 mm dimension. These dimensions were chosen to ensure adequate width to support the drilling process and facilitate real-time temperature monitoring of the drill near a side wall using an IR camera. To improve temperature detection, one of the workpiece's two 200 mm × 40 mm faces was painted black to enhance emissivity. This painted face was positioned directly perpendicular to the camera's line of sight. Figure 1 presents the experimental setup (Table 3).

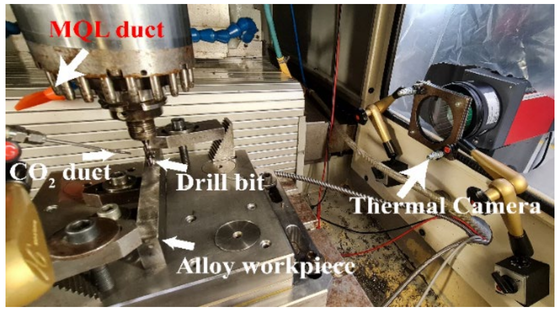

Figure 1. The image shows the workpiece, drilling tool, coolant duct, MQL duct, and infrared camera

Table **3**. Experimental results for *VB*, *R*a, *τ*, *F*, and T_{max}

Material	Lubro-Cool	*V*c (m/min)	*VB* (µm)	*R*a (µm)			*τ* (N-mm)			*F* (N)			T_{max} (˚C)		
				H1	H2	H3	H1	H2	H3	H1	H2	H3	H1	H2	H3
Incoloy 825	Dry	18	-	-	-	-	9,848	-	-	2,316	-	-	-	-	-
	Dry	12	185	0.87	-	-	12,675	-	-	2,607	-	-	218.0	-	-
	Dry	9	177	-	-	-	10,296	-	-	2,616	-	-	169.5	-	-
	C-I	12	-	-	-	-	2,376	-	-	1,719	-	-		-	-
	C-I	22	-	-	-	-	4,593	5,178	-	1,880	2,075	-	6.1	-	-
	CL	18	29.5	0.93	0.30	0.43	4,230	3,068	3,068	2,075	1,544	2,075	37.2	31.6	29.6
	CL	26	19.5	1.14	1.35	0.44	3,449	3,562	2,955	1,609	1,455	1,320	38.1	35.3	34.8
	L-I	18	31.0	0.91	0.39	0.67	4,371	4,311	4,433	1,434	1,438	1,435	56.1	56.3	56.2
	C-E	18	27.3	0.85			4,055			1,904			124.9		
	CL	32	202	1.21	1.58	1.10	5,501	8,395	7,616	2,629	2,739	2,628	94.6	113.7	123.3
Inconel 718	Dry	12	-	-	-	-	-	-	-	-	-	-	212	-	-
	C-I	12	27	0.74	0.61	0.53	4,336	4,192	4,141	1,555	1,562	1,589	7	7	6
	CL	18	27	0.407	1.25	1.54	3,736	3,825	3,811	1,334	1,312	1,286	49	51	50
	CL	26	33	1.15	0.68	0.81	3,891	3,960	4,870	1,290	1,404	2,039	53	54	81
	L-I	18	52	0.92	0.75	0.76	4,460	4,514	4,469	1,398	1,342	1,272	58	56	54
	C-E	18	267	0.57	0.41	0.75	5,143	4,462	4,233	1,744	1,571	1,502	48	47	44
	CL	32	27	1.33	1.06	0.86	6,946	4,322	4,136	2,472	2,090	2,167	102	38	41
Waspaloy	Dry	18	-	-	-	-	10	-	-	2,318	-	-	254	-	254
	Dry	12	178	0.84	-	-	12,706	-	-	2,141	-	-	201	-	-
	C-I	22	18	0.89	-	-	4,694	-	-	1,914	-	-	4	-	-
	C-I	26	-	-	-	-	4,867	-	-	1,977	-	-	-	-	-
	CL	12	22.5	0.38	0.83	0.42	5,844	4,179	3,801	1,459	1,348	1,094	47	41	40
	CL	18	24	0.51	0.40	0.60	4,596	3,780	3,481	1,440	1,336	1,332	45	45	43
	CL	26	46.5	1.36	0.95	1.11	7,523	4,480	4,481	2,411	1,602	1,512	93	54	51

The Mahr Marsurf M300C was used to measure the surface roughness of the drilled holes. Tool wear was assessed with a Keyence VHX-950F digital optical microscope. Flank wear measurements were taken from three evenly distributed locations on the lips' surfaces, and the average of these measurements was used to calculate the VB value. An InfraTec GmbH Image IR 8300 Z infrared camera, equipped with a 30x zoom lens, continuously monitored the temperature of the sidewall throughout the drilling process. The black-painted side's emissivity coefficient (ε) was consistently maintained at 0.98. Force measurements during the experiments were conducted using a Kistler 9255B piezoelectric dynamometer in conjunction with an NI terminal block BNC-2110. In each experimental run, three blind holes were drilled to a depth of 18 mm each using either cryogenic cooling, micro-lubrication, or a combination of both, with a fixed feed rate of 0.1 mm/rev for all runs.

4. Results and Discussion

Table 3 presents the experimental results for all five responses. It is important to note that the table shows aggregated results for the three holes in the tool wear category (VB), as it is challenging to measure tool wear after drilling each hole and continuing with the run. In contrast, results for the individual holes (H1, H2, and H3) are provided for the other four responses. A hyphen in a cell and an empty cell indicate that the tool did not last until that hole and the next hole in the sequence were not chosen to be cut, respectively.

4.1. Tool Wear

Significant tool wear was observed under dry drilling conditions due to excessive friction and thermal load, which led to rapid tool failure. Thus, the dry option can quickly be ruled out of consideration for sustainable drilling options. Through-the-tool CO_2 cooling (C-I) resulted in tool breakage, particularly at the cutting edges, due to brittleness induced by excessive cooling at the tool's exit point. Throttling of a high-pressure CO_2 jet right at the coolant holes located at the cutting lips overcools the bottom part of the drilling tool, inducing a significant level of brittleness. As a result, a frail structure gives in to the excessive shear load of cutting a hole and shatters into pieces near the bottom. Cutting even the first of the three planned holes was challenging using the through-the-tool cryogenic cooling technique.

In contrast, the hybrid lubri-cooling option (CL) showed minimal tool wear, especially at an 18 m/min cutting speed, where it successfully sustained three consecutive drill cycles. This method achieved a balanced cooling and lubrication effect, extending tool life and reducing the wear rate more effectively than any other tested method. A through-the-tool supply of micro-lubrication ensured the highest probability of lubricant droplets penetrating the shear zones and favorably altering the tribological conditions. This, coupled with an appropriate magnitude of cooling (external cryogenic), enough to dissipate excessive heat out of the in-process hole, provided the most suitable conditions for elongating the tool life.

Figure 2 shows optical micrographs of the cutting lips from the tools used in the selected runs. The images show gradual mechanical wear, with higher intensity near the chisel edge. Signs of microchipping are also apparent, especially in Images B and E. This suggests that cutting the harder alloy (Inconel 718) and processing at a higher cutting speed lead to chipping-based tool damage. Moreover, severe adhesion of work material on the tool's surface was evident in all the runs, so much so that the chips got badly entangled in the drill grooves in the tests carried out at the higher levels of cutting speed.

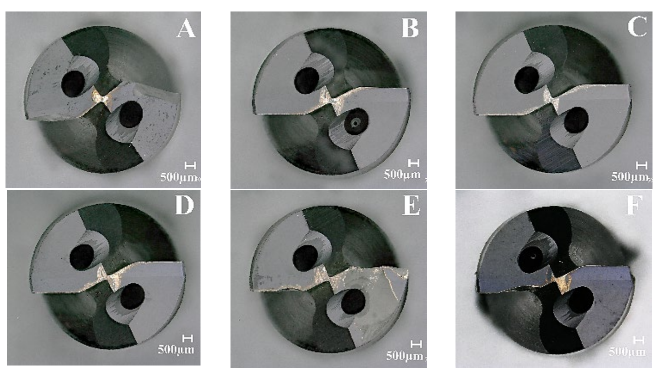

Figure 2. Optical micrographs of the cutting lips taken from the drills used in the following runs: (A) Incoloy 825, C-E, 18 m/min, H1; (B) Incoloy 825, CL, 26 m/min, H3 (C) Waspaloy, CL, 12m/min, H3 (D) Waspaloy, CL, 26 m/min, H3 (E) Inconel 718, C-E, 32 m/min, H3 (F) Inconel 718, CL, 18 m/min, H3

4.2. Thrust Force and Torque

The data related to F and τ are presented in Table 3. High thrust forces and cutting torques were recorded in dry drilling because of the lack of lubrication and rapid tool damage caused by the absence of a heat dissipation mechanism. The bluntness of the lips and the change in the cutting-edge geometry caused hikes in the two measures early in the cutting process. The hybrid lubri-cooling approach, particularly at the lower levels of cutting speed, resulted in consistently lower thrust forces and torques, indicating smoother cutting operations. The through-the-tool micro-lubrication method also performed well but struggled to maintain these low forces and torques at higher cutting speeds. Overall, the hybrid cooling approach effectively minimized the force and torque requirements, reducing energy demands and improving cutting efficiency.

Regarding the effect of work material, there is no significant difference between the three materials in terms of thrust force. The impact of cutting speed is more significant on Inconel 718 than on the other two alloys. Likewise, the choice of the lubri-cooling approach has a more substantial effect on the torque experienced by Incoloy 815 and Waspaloy than that by Inconel 718. Figure 3 shows thrust force and cutting torque micrographs for the selected three runs. The F_z curves related to the drilling of Inconel 718 and Waspaloy (images A and B) show that the force component held its magnitude after achieving the complete penetration of the drill's conical part. However, the curve related to the cutting of Incoloy 825 shows a persistent, gradual increase in the force component's curve, indicating an intensified wear effect of the highest level of cutting speed.

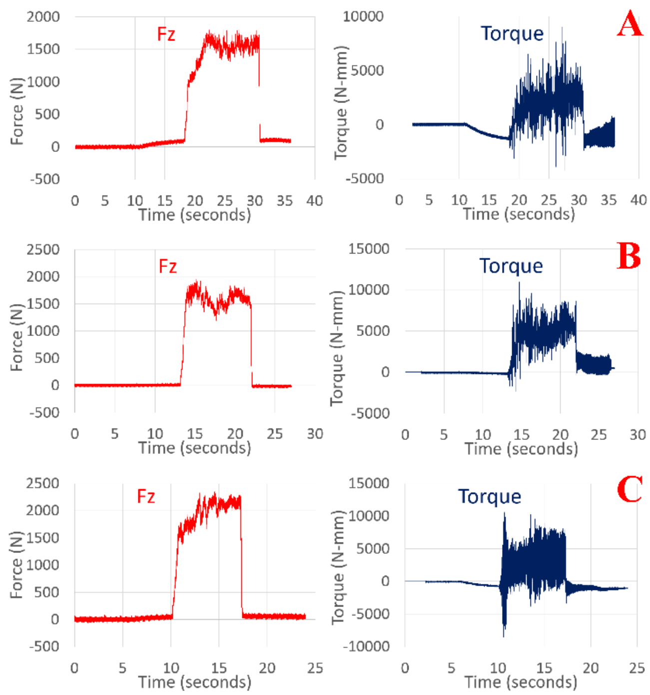

Figure 3. Thrust force and cutting torque micrographs for the following runs: (A) Inconel 718, L-I, and 18 m/min; (B) Waspaloy, CL, and 26 m/min; and (C) Incoloy 825, CL, and 32 m/min. All the micrographs are associated with hole number 2 of the corresponding run.

4.3. Surface Roughness of the Holes

The experimental data related to *R*a, as shown in Table 3, suggest that the surface finish significantly depends on the cooling and lubrication strategy used. The hybrid lubri-cooling approach yielded the lowest surface roughness of all the lubri-cooling methods used, especially at the cutting speeds of 18 and 26 m/min. The combined cooling and lubrication effects minimized the frictional effects at the tertiary shear zone and eased chip adhesion on the cutting lips. Dry drilling yielded high surface roughness because of excessive friction, chip adhesion, and rapid tool wear. Meanwhile, the pure micro-lubrication (L-I) approach showed favorable but less consistent results in maintaining surface quality than the hybrid approach. No significant difference regarding surface quality is observed between the three superalloys. In a nutshell, it can be stated that the drilling of nickel-based superalloys can achieve the best surface quality when the process is carried out at a low cutting speed and under hybrid lubri-cooling conditions.

4.4. Temperature Profile of the Sidewall

This response reflects the comparative temperature conditions near the cutting regions. By monitoring the temperature profile of the side wall existing close to the hole axis, the accumulated heat, as a balance between the heating effect caused by the cutting of the work material and the cooling effect caused by the coolant, can be estimated. T_{max}, the maximum temperature reached on the side wall during the drilling cycle, reflects the efficacy of the heat dissipation system and the viability of the cutting parameters employed.

Some vital insights can be extracted by analyzing the T_{max} data provided in Table 3. Heat dissipation is most effective with the hybrid lubri-cooling method, which maintains stable temperatures across different cutting speeds, even at the highest level of cutting speed. Such control over cutting temperature curbed the thermal degradation of the drilling tool, inducing viability in the hole-making process. Although minimal data are available regarding the through-the-tool CO_2 cooling approach because of the non-viability of the process, it can be deduced that the approach led to the lowest temperatures of all the lubri-cooling methods. Such low temperatures acted against the objective and caused catastrophic failures of the tools. The external cryogenic cooling method (C-E) provided some cooling benefits; it was less effective at higher speeds due to flow limitations and direct inaccessibility to the cutting zones. The cooling effect provided by this approach was only due to the conduction through the drill's body. Dry drilling yielded the highest temperatures, causing rapid tool wear, tool material softening, and increased adhesion and chipping. These findings underscore the hybrid method's advantage in managing the thermal environment effectively, enabling extended tool life and more consistent cutting performance. Figure 4 shows stills from the temperature profile recordings of the selected runs.

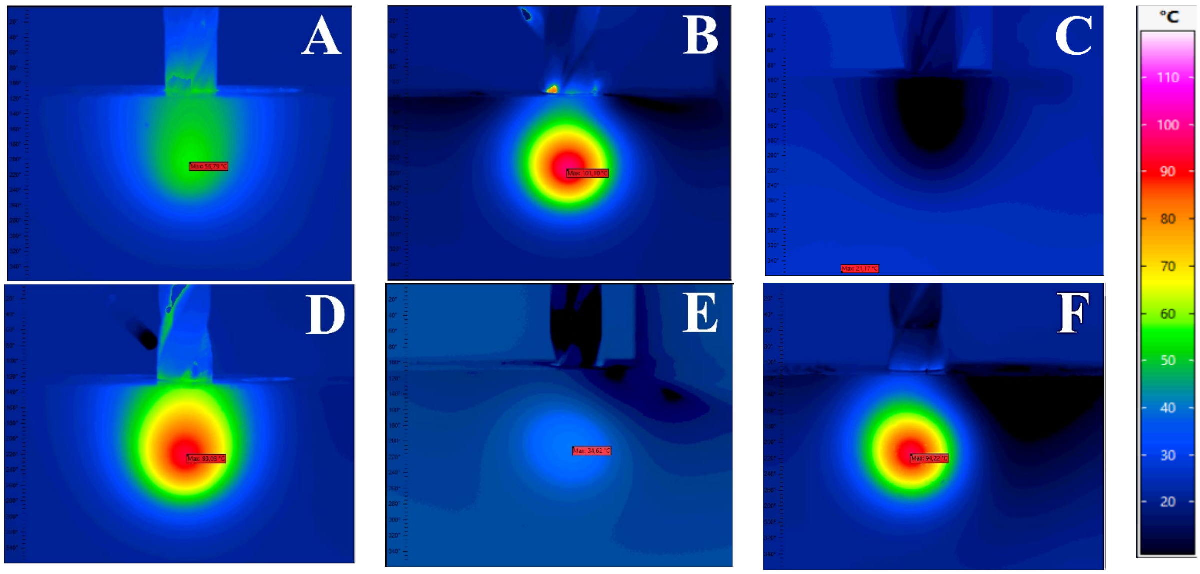

Figure 4. Images captured at various stages of the drilling cycles, taken from the temperature profile clips of the following runs: (A) Inconel, L-I, 18m/min; (B) Inconel, CL, 32m/min; (C) Waspaloy, C-I, 22m/min; (D) Waspaloy, CL, 26m/min; (E) Incoloy, CL, 18m/min; and (F) Incoloy, CL, 32m/min. All the stills are associated with hole number 1 of the corresponding run.

4.5. Discussion

The study evaluates new cooling and lubrication methods for countering the problems faced in the drilling of Incoloy 825, Waspaloy, and Inconel 718. As observed in the experimental runs, dry drilling resulted in tool breakage due to adhesion and microchipping. This was expected since dry drilling caused severe chip entanglement and high thermal loads due to the lack of any cooling or lubrication mechanism. Through-the-tool cryogenic cooling also caused premature tool breakage due to excessive cooling, which rendered the tool's body close to the cutting-edge very brittle. A system constraint did not allow the coolant's flow rate reduction to lower the cooling potential. In contrast, the external CO_2 application provided better control over the flow rate and cooling effectiveness, though the mode of heat removal in this case relied solely on conduction.

Regarding tool damage, the hybrid lubri-cooling approach applied at 18 m/min cutting speed showed the mildest tool wear. Regarding thrust force and torque, the same lubri-cooling approach applied at 18 m/min cutting speed generated the best results, yielding the second-lowest thrust force and the lowest torque of all the runs. As for surface roughness, the hybrid lubri-cooling approach achieved the lowest overall values. Although the through-the-tool cryogenic cooling yielded the lowest sidewall temperature, it proved fatal for the process sustainability as the tools fractured prematurely giving in to the high cutting torques because of the induced brittleness. The hybrid lubri-cooling method maintained the temperature in an acceptable range even at higher cutting speeds, preventing excessive tool wear and maintaining consistent cutting conditions.

In a nutshell, the hybrid lubri-cooling approach, i.e., external CO_2 plus through-the-tool micro-lubrication (LC), is recommended for drilling the nickel-based superalloys because it reduces thrust force and cutting torque, subsides tool wear rate, and improves surface finish. It enables successful drilling at higher cutting speeds while ensuring effective cooling and lubrication, making the process more efficient and reliable for these difficult-to-cut materials.

5. Conclusion

This study evaluated innovative cooling and lubrication methods for their effectiveness in drilling three nickel-based superalloys. The results show that the hybrid lubri-cooling method, realized by combining an external supply of throttling CO_2 with a through-the-tool supply of micro-lubrication, outperformed the other approaches, achieving the optimal balance of slashed tool wear, reduced cutting force and torque, and improved surface finish. This method is particularly effective at higher cutting speeds, where other methods, including dry drilling and through-the-tool CO_2 cooling, could not deliver due to rapid tool damage.

These findings highlight the potential of hybrid lubri-cooling strategies to improve machining efficiency and sustainability for difficult-to-machine materials like Incoloy 825, Waspaloy, and Inconel 718. By effectively managing heat removal and lubrication at the shear zones, the hybrid approach provides a reliable solution for industrial applications that demand high precision and productivity, offering a pathway toward more sustainable and cost-effective machining practices.

References

Busch, K., Hochmuth, C., Pause, B., Stoll, A. and Wertheim, R., Investigation of cooling and lubrication strategies for machining high-temperature alloys. *Procedia CIRP*, vol. 41, pp.835-840, 2016.

Elshwain, A. E. I., and Redzuan, N., Effect of cooling/lubrication using cooled air, MQL + cooled air, N_2 and CO_2 gases on tool life and surface finish in machining – a review. *Advanced Materials Research*, vol. *845*, pp. 889–893. 2013.

Ezugwu, E.O., Key improvements in the machining of difficult-to-cut aerospace superalloys. *International Journal of Machine Tools and Manufacture*, vol. *45*, pp.1353-1367, 2005.

Guo, S., Li, C., Zhang, Y., Yang, M., Jia, D., Zhang, X., Liu, G., Li, R., Bing, Z. and Ji, H., Analysis of volume ratio of castor/soybean oil mixture on minimum quantity lubrication grinding performance and microstructure evaluation by fractal dimension. *Industrial Crops and Products*, vol. 111, pp.494-505, 2018.

Iqbal, A., Zhao, G., Zaini, J., He, N., Nauman, M.M., Jamil, M. and Suhaimi, H., Sustainable hole-making in a titanium alloy using throttle and evaporative cryogenic cooling and micro-lubrication. *Journal of Manufacturing Processes*, vol. 67, pp.212-225, 2021.

Iqbal, A., Saelzer, J., Abu Bakar, M. S., Biermann, D., Khan, A. M., Sicking, M., and Nauman, M. M., Side-milling of Incoloy 825 under pulsed and continuous modes of cryogenic cooling. *Journal of Manufacturing Processes*, vol. 104, pp. 246–256, 2023.

Iqbal, A., Saelzer, J., Ali, K., Biermann, D., Sicking, M., Bakar, M.S.A., Khan, A.M. and Nauman, M.M., Investigations on pulsed and continuous supply of a cryogenic medium in milling of Waspaloy and Inconel 718 under various lubri-cooling environments. *The International Journal of Advanced Manufacturing Technology*, vol. 132, pp. 3027-3046, 2024.

Jemielniak, K. Review of new developments in machining of aerospace materials. *Journal of Machine Engineering*, vol. 21, pp. 22–55, 2021.

Osman, K.A., Ünver, H.Ö. and Şeker, U., Application of minimum quantity lubrication techniques in machining process of titanium alloy for sustainability: a review. *The International Journal of Advanced Manufacturing Technology*, vol. *100*, pp.2311-2332, 2019.

Pimenov, D. Yu., Da Silva, L. R. R., Machado, A. R., França, P. H. P., Pintaude, G., Unune, D. R., Kuntoğlu, M., & Krolczyk, G. M., A comprehensive review of machinability of difficult-to-machine alloys with advanced lubricating and cooling techniques. *Tribology International*, vol. 196, 109677, 2024

Rajguru, R., and Vasudevan, H., A review and analysis of the machining process involving nickel-based super alloy. In H. Vasudevan, V. K. N. Kottur, & A. A. Raina (Eds.), *Proceedings of International Conference on Intelligent Manufacturing and Automation* (pp. 425–432). Springer Singapore, 2019.

Panigrahi, R., Panda, A., Kumar Sahoo, A., and Kumar, R., Machining performance measures of high temperature heat resistant super alloys: A review. *Materials Today: Proceedings*, vol. 18, pp. 4524–4530, 2019.

Rahim, E.A., Ibrahim, M.R., Rahim, A.A., Aziz, S. and Mohid, Z., Experimental investigation of minimum quantity lubrication (MQL) as a sustainable cooling technique. *Procedia CIRP*, vol. *26*, pp.351-354, 2015.

Ramanujam, R., Vignesh, M., Tamiloli, N., Sharma, N., Srivastava, S. and Patel, A., Comparative evaluation of performances of TiAlN, AlCrN, TiAlN/AlCrN coated carbide cutting tools and uncoated carbide cutting tools on turning Inconel 825 alloy using Grey Relational Analysis. *Sensors and Actuators A: Physical*, vol. *279*, pp.331-342, 2018.

Ray, A., Cutting fluid selection for sustainable design for manufacturing: An integrated theory. *Procedia Materials Science*, vol. 6, pp.450-459, 2014.

Sivadasan, P., Sharma, G. S., Rout, I. S., and Pal Pandian, P., A review on influence of cutting fluid on improving the machinability of Inconel 718. In A. Praveen Kumar, T. Dirgantara, & P. V. Krishna (Eds.), *Advances in Lightweight Materials and Structures* (Vol. 8, pp. 497–504). Springer Singapore, 2020.

Thakur, D.G., Ramamoorthy, B. and Vijayaraghavan, L., Study on the machinability characteristics of superalloy Inconel 718 during high speed turning. *Materials & Design*, vol. 30, pp.1718-1725, 2009.

Yıldırım, Ç.V., Kıvak, T., Sarıkaya, M. and Şirin, Ş., Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL. *Journal of Materials Research and Technology*, vol. *9*, pp.2079-2092, 2020.

Zhu, D., Zhang, X. and Ding, H., Tool wear characteristics in machining of nickel-based superalloys. *International Journal of Machine Tools and Manufacture*, vol. 64, pp.60-77, 2013.

Biographies

Asif Iqbal is an associate professor of manufacturing systems engineering at the Faculty of Integrated Technologies, University of Brunei Darussalam, Brunei. He completed his Mechanical Manufacturing and Automation doctorate in 2006 at Nanjing University of Aeronautics & Astronautics, China. Dr. Iqbal has served a state-owned technical R&D organization in Pakistan for 7 years. Since 2010, he has associated himself with teaching and research. He has served leading universities in four countries as a faculty member before joining the University of Brunei Darussalam. He has worked on various funded research projects on sustainable manufacturing, cryogenic machining, and intelligent manufacturing. Since 2016, Dr. Iqbal has collaborated with Nanjing University of Aeronautics & Astronautics, China, on Key Technology in Sustainable Manufacturing under the 111 project. His further research interests lie in high-speed machining, cellular manufacturing systems, additive-subtractive hybrid manufacturing, incremental forming, fuzzy modeling, and expert systems.

Jannis Saelzer graduated with a bachelor's in mechanical engineering from the Technical University (TU) of Dortmund, Germany, in 2018. From 2015 to 2018, he served as a student assistant at the Institute of Machining Technology (ISF) at the same university, where he realized his interest in machining science and technology. In 2019, he was promoted to the rank of Research Associate. At his new designation, he gained a deeper involvement in research related to cutting difficult-to-cut alloys, cryogenic machining, and modeling and simulation of machining processes. Since 2022, he has been serving the ISF, TU Dortmund, as the department head for the fundamentals and modeling in cutting technology, where he is overseeing projects related to efficient modeling of chip formation in orthogonal cutting and other areas such as tribology and lubrication.

Muhammad Izzuddin Sabaruddin graduated from Universiti Brunei Darussalam (UBD) in 2022 with a bachelor's degree in general engineering, concentrating on manufacturing systems. In 2023, he was employed at the Faculty of Integrated Technologies of the UBD as a research assistant, where he has been assisting Dr. Asif Iqbal on his research projects related to additive-subtractive hybrid manufacturing of consolidated parts made of titanium and nickel alloys and cryogenic machining of difficult-to-cut alloys. He aspires to earn higher qualifications in the field of advanced manufacturing from a reputed university in an industrialized country.

Malik M. Nauman is a distinguished academic and researcher with over 11 years of experience in manufacturing, energy engineering, innovation, and entrepreneurship. He has worked at various universities worldwide, including in Turkey and Saudi Arabia, and currently serves as an Associate Professor and Deputy Dean at the Faculty of Integrated Technologies, Universiti Brunei Darussalam. Dr. Nauman has published numerous papers in prestigious international journals and conferences, focusing on the 2D/3D printing of energy devices, thin-film solar cells, memristors, and the inverse heat and mass transfer estimation. His active participation in workshops and seminars demonstrates his commitment to academic excellence. His research interests span energy devices, image processing, and shape memory alloys, making him a valuable member of the academic community.