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Milling of nickel-based superalloys using throttle cryogenic cooling and micro-lubrication

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Abstract. Nickel-based alloys are known to mount intense heat around the cutting edges of the cutting tool owing to their high yield strength, comparatively low thermal conductivity, and a significant seizure of the chip at the rake face even at low cutting speeds. Their sustainable machining demands a highly effective heat dissipation system. Due to its rich cooling potential, the compressed CO_2-based throttle cryogenic cooling system is a prime contender. The presented work seeks a sustainable milling solution for the cutting of the following three nickel-rich allows using the combination of throttle cryogenic cooling and minimum quantity of lubrication: Inconel 718, Incoloy 825, and Waspaloy. The experimental study quantifies the effects of the lubri-cooling approach and cutting speed on tool wear, cutting forces, and workpiece surface roughness. The novelty of the work lies in the mutual comparison of the machinability of the three alloys of nickel and the application of the cryogenic coolant in the form of pulses in addition to the conventional mode of continuous stream. The analyses of the experimental results suggest that the pulsed mode of the coolant, especially in combination with the lubricant, outperforms the continuous mode of the coolant's supply regarding cutting forces and work surface roughness. Additionally, the study has yielded mixed results regarding tool wear for different combinations of workpiece material and cutting speed. Nonetheless, dry milling of the three alloys proved to be absolutely unsustainable in comparison to either of the two modes of throttle cryogenic cooling, with or without the application of micro-lubrication.

Introduction

Nickel-based superalloys are seeing a steady increase in their demand for making engineering components used in extreme heat and pressure environments. They find application mainly in the making of gas turbines, aerospace components, and automotive parts. The very mechanical properties that embellish the alloys for intense applications are also responsible for their poor workability in mechanical manufacturing, and the domain of machining is no exception. Machining is the only viable method to yield the dimensional accuracy and surface finish required for the engineering components used in the applications described above. Considering the high yield strengths and their retention at high temperatures, comparatively low thermal conductivities, intense engagement of the chip with the rake face, and adhesivity with the tool surface, viable machining of nickel-based superalloys requires a highly effective heat dissipation mechanism [1]. Emulsion-based flood coolants are not up to the mark due to their low cooling potential. The situation calls for the application of cryogenic cooling. A very low working temperature enables a cryogenic coolant to subdue an intense heat flux around the cutting edges. Moreover, it does not create any unsustainable wastage issues as is the case with flood coolants. To work out the research gap in this context, a brief literature review is provided below.

The machinability index of nickel-based alloys is around 35 on a scale from 0 to 100, making them exceedingly more difficult to cut than a plain carbon steel [2]. The machinability index of AISI 1112 plain carbon steel is taken as 100. In addition to high strengths, their low thermal conductivities also contribute to tool wear by channeling a high proportion of process heat to the cutting tool [3]. These alloys are also known for intense work hardening, which means they pose an increased difficulty to cutting as the machining process progresses [4]. Hybrid cryogenic cooling (using liquid nitrogen) and lubrication (MQL) are used in the machining of Inconel 718 [5]. The study reported that the application of the hybrid environment ensures the longest tool life. Another study carried out on Cryo-MQL machining of Inconel 718 reported the achievement of better surface finish, lower cutting temperature, and milder tool wear in comparison to dry, MQL, and even cryogenic machining [6]. Additively manufactured nickel-based parts were machined under hybrid cryogenic cooling [7]. It was reported that the hybrid lubri-cooling approach remains highly effective in curbing tool wear at high cutting speeds. In another investigation, a nickel-chromium alloy (Nimonic 80A) was machined under various cryogenic cooling and lubrication environments [8]. The cryogenic cooling yielded a significantly better surface finish as compared to dry and flood cooling but not as good as that by micro-lubrication. Inconel 718 and Waspaloy were face-turned under emulsion coolant pressures of 6 and 80 bars [9]. The high-pressure cooling was found to reduce the flank wear on both alloys. High alloy adhesion was also reported on the tooltip. The micro-crack formation, shedding of the coating on the two tool faces, and tool-tip chipping are the major modes of tool failure in the micro-milling of Inconel 718 using coated carbide end mills [10]. A study has emphasized that liquid nitrogen-based inner injection cooling is more advantageous concerning the machining performance measures than the external application in the milling of nickel-based alloys [11]. An experimental study was carried out for comparing the performance of LN_2 and CO_2 for enhancing tool life in machining of Inconel 718. The study reported that the former remained worse than the former in this regard whereas the conventional lubrication technique outperformed both.

The review leads to a gap asking for exploring application of various modes cryogenic cooling with and without the addition of micro-lubrication in the machining of nickel-based superalloys. Considering the success of hybrid lubri-cooling attained in the machining of other difficult-to-cut materials calls for its application in the milling of nickel alloys as well. The current study investigates the efficacy of applying compressed CO_2-based throttle cryogenic coolant, with and without the addition of micro-lubrication, in the milling of the following superalloys of nickel: Inconel 718, Incoloy 825, and Waspaloy. Specific to the operational mechanism of the milling process, characterized by periodic engagement and disengagement of the cutting edges with the workpiece material, the effectiveness of the throttle cryogenic coolant will be tested in pulsed and continuous modes of supply. In short, the presented work targets underscoring the potential of cryogenic cooling-based lubri-cooling approach in making the machining of nickel alloys sustainable.

Experimental Work

This section provides details on the milling experiments performed, including the experimental setup, design of experiments, inputs and responses, tooling, and workpiece materials.

Workpiece Materials and Milling Tools

The three workpiece materials tested in the work are Inconel 718, Incoloy 825, and Waspaloy. The first one is a commonly used high-strength, corrosion-resistant nickel-chromium alloy. It is a precipitation-hardened material having noteworthy proportions of iron, molybdenum, niobium, and along with smaller quantities of titanium and aluminum. High strength, extreme toughness, and intense work-hardening render this superalloy a difficult-to-cut material. Incoloy 825, a relatively lesser-known material, is a heat-treatable nickel-iron-chromium alloy with lesser but significant amounts of molybdenum, titanium, and copper. It is different from Inconel 718 in terms of a notably smaller proportion of nickel, which gives way to a larger share of iron and makes it relatively easier to machine. Waspaloy, another superalloy of nickel, is closer to Inconel 718 as compared to Incoloy 825 with respect to chemical composition and mechanical characteristics. Likewise, Waspaloy is precipitation-hardened and possesses high high-temperature strength and excellent corrosion resistance. Tables 1 and 2 present comparative analyses in terms of chemical composition and mechanical properties, respectively of the three superalloys.

Table 1. Chemical compositions of Inconel 718, Incoloy 825, and Waspaloy (the numbers are in percentage)

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

Table 2. Mechanical properties of Inconel 718, Incoloy 825, and Waspaloy

	Tensile Strength	Yield Strength	Elongation	Hardness	Themal Conductivity
Incoloy 825	703 MPa	340 MPa	39 %	22 HRc	11.1 W/m.K
Inconel 718	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

Ceramic coated (multiple layers of TiN and TiAlN) tungsten carbide side-and-end milling cutters possessing a diameter (D), cutting length (l_c), total length (l), helix angle (λ), and the number of teeth (z) of 8 mm, 40 mm, 100 mm, 30°, and 4, respectively, are used in this study. Ceramic coatings, due to their extreme hardness, add to the wear resitance of the carbide tools. A new milling tool is used for each experiment.

Design of Experiments

The following three inputs are controlled:

a) Workpiece material. The three levels of this categorical parameter are Inconel 718, Incoloy 825, and Waspaloy.
b) Cutting speed. The two levels of this input are 80 m/min and 120 m/min.
c) Cooling and lubrication mechanism. The five levels of this categorical parameter are dry, continuous stream of the throttle cryogenic coolant (th_c), pulsed stream of the throttle cryogenic coolant (th_p), continuous stream of the throttle cryogenic coolant with parallel addition of micro-lubrication (th_c-l), pulsed stream of the throttle cryogenic coolant with parallel addition of micro-lubrication (th_p-l).

A full-factorial design of experiments yields 30 (= 3 × 2 × 5) experimental runs. For each run, the following three responses are measured:

a) Average width of flank wear land (VB - µm).
b) Three orthogonal components of cutting forces (F_x, F_y, and F_z – N). The components F_x and F_z are aligned with the feed direction and the cutter's axis, respectively. The third component is perpendicular to the other two.
c) Average arithmetic roughness of the machined surface (R_a - µm)

The throttle cryogenic cooling of the milling area is carried out by transporting compressed CO_2 from a cylinder through a metallic tube at a mass flow rate of 2.2 kg/h and throttling it out through an orifice of 1.5 mm diameter. The throttling fluid absorbs heat from its vicinity following the Joule-Thomson phenomenon. The distinction between the pulsed and continuous supply of the cooling fluid is made by a control device that cyclically opens and closes the fluid delivery valve after every fixed period for the former. The pulse frequency of the pulsated coolant supply is 30 Hz. The device is placed outside the machine tool and is activated manually. For the continuous supply, the valve remains open during the entire cutting duration of the run. For the runs involving micro-lubrication (th_c-l and th_p-l), the aerosol is supplied through a separate tube to the cutting region. The aerosol is a biodegradable oil atomized into a flow of air compressed to 6 bars. The supply of micro-lubrication is not pulsed for any experimental run.

Experimental Setup

The experiments are performed on a CNC milling machine, Chiron FZ 12S Magnum. The milling tools are held in a shrink-fit holding mechanism to grant more accessibility of the cutting area to the cooling and lubrication nozzles. A digital optical microscope is used to measure the tool wear. The width of flank wear land is determined at three locations on each of the four edges of the used milling tool. The VB is then evaluated by taking the mean of the 12 readings. The R_a of the machined surface is measured using a surface roughness meter, Mahr Marsurf M300C. Finally, the machining forces are determined using a Kistler-based dynamometer (type 9255B) and a multichannel charge amplifier. The force readings are analyzed using DIAdem, a numeric data management software. Fig. 1 presents the experimental setup.

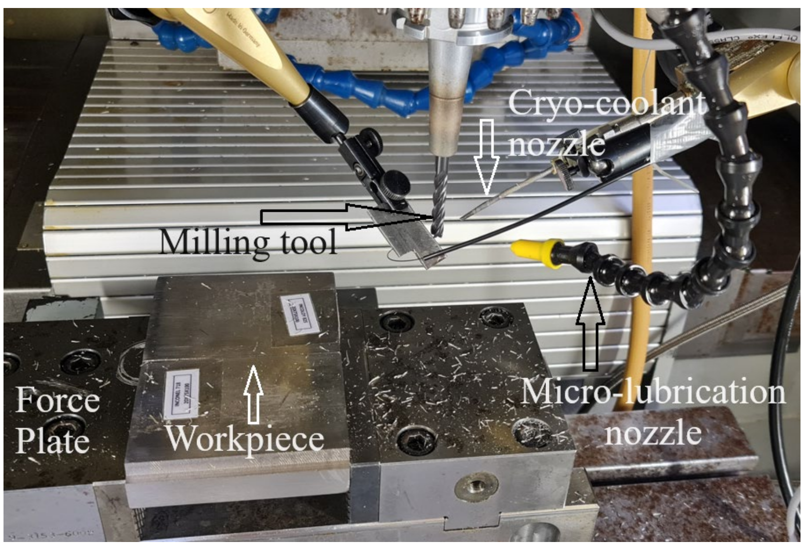

Fig. 1. The experimental setup

Each of the 30 experiments is completed in three passes maintaining the total length of cut equal to 300 mm. The radial and axial depths of cut are kept at 0.2 mm and 8 mm, respectively. The feed rate is fixed to 0.1mm/tooth and down-milling is selected as the milling orientation. Lastly, the tool overhang for each run is kept at 52 mm.

Experimental Results and Analyses

Table 3 presents the results obtained from the experiments regarding tool wear, machining forces, and work surface roughness. The upcoming sub-sections discuss the tabulated results and their analyses.

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Tool Wear

The fifth column of Table 3 presents the measured values of VB for all 30 runs of the three alloys tested at the two different speeds and 5 lubri-cooling approaches. For Incoloy 825, apart from the dry test carried out at the high level of cutting speed, the VB results do not show a strong dependence on cutting speed. Similarly, both VB values of Inconel 718 and Waspaloy show a similar outcome regardless of the cutting speed, however, the lubricated test shows a significant difference at the lower cutting speed especially with Waspaloy.

Table 3. Experimental results regarding tool wear, machining forces, and surface roughness

S/ No.	Material	Lubri-Cooling	Cutting speed (m/min)	*VB* (μm)	F_x (N)	F_y (N)	F_z (N)	R_a (μm)
1	Incoloy 825	Dry	120	498.98	197.84	258.3	141.34	3.07
2	Incoloy 825	Dry	80	78.94	173.56	194.22	88.39	2.42
3	Incoloy 825	th_c	120	40.68	121.19	145.14	68.15	2.757
4	Incoloy 825	th_c	80	45.49	106.77	122.5	48.66	2.147
5	Incoloy 825	th_p	120	67.96	122.9	145.94	57.97	1.143
6	Incoloy 825	th_p	80	92.22	165.65	169.8	90.94	2.33
7	Incoloy 825	th_c-*l*	120	57.31	120.87	148.07	68.23	1.703
8	Incoloy 825	th_c-*l*	80	53.61	117.13	124.51	43.87	1.885
9	Incoloy 825	th_p-*l*	120	60.76	113.29	140.74	59.96	1.386
10	Incoloy 825	th_p-*l*	80	61.87	115.54	134.03	49.13	0.974
11	Inconel 718	Dry	120	88.29	153.63	201.24	97.61	1.515
12	Inconel 718	Dry	80	76.81	145.86	177.47	60.03	1.396
13	Inconel 718	th_c	120	109.56	161.8	206.83	101.32	2.313
14	Inconel 718	th_c	80	86.77	146.42	167.32	60.73	1.864
15	Inconel 718	th_p	120	206.39	172.63	198.66	103.42	1.632
16	Inconel 718	th_p	80	83.07	132.8	149.87	56.54	2.306
17	Inconel 718	th_c-*l*	120	62.95	165.47	189.44	89.62	2.425
18	Inconel 718	th_c-*l*	80	76.71	133.67	141.8	47.67	1.439
19	Inconel 718	th_p-*l*	120	63.79	178.75	199.62	96.47	1.266
20	Inconel 718	th_p-*l*	80	58.11	137.5	133.59	49.75	0.907
21	Waspaloy	Dry	120	107.10	158.39	208.98	78.06	1.893
22	Waspaloy	Dry	80	105.20	148.33	186.72	60.17	1.232
23	Waspaloy	th_c	120	590.26	184.57	186.82	88.62	1.444
24	Waspaloy	th_c	80	79.08	159.44	157.79	51.03	2.584
25	Waspaloy	th_p	120	218.44	172.49	188.13	92.18	2.038
26	Waspaloy	th_p	80	60.01	164.36	163.75	53.46	2.582
27	Waspaloy	th_c-*l*	120	154.42	180.85	193.53	99.21	1.499
28	Waspaloy	th_c-*l*	80	74.56	168.23	170.08	45.78	0.972
29	Waspaloy	th_p-*l*	120	94.92	152.5	172.48	92.95	2.752
30	Waspaloy	th_p-*l*	80	70.86	136.89	149.05	52.03	1.457

Continuous supply of throttling CO_2 (th_c) yields milder tool wear than pulsing the supply (th_p) in Incoloy 825. The continuous mode provides almost double the cooling potential compared to the pulsed mode, with the addition of lubrication, the pulsed mode (th_p-*l*) is more effective in checking tool wear as the lubricant successfully made its way to the shear zone through the punctuated supply of coolant. In contrast to the continuous mode (th_c-*l*), the coolant acts as a barricade from the lubricant to be delivered and even compromises the coolant's efficacy resulting in the intensification of the tool wear. For Incoloy 825 the th_c mode is the lubri-cooling mode that is effective in checking the tool wear at both levels of cutting speed.

For Waspaloy, high cutting speed with the th_c mode resulted in the maximum tool wear whereas at low cutting speed, it had the minimum tool wear with the th_p mode. The result shows there is higher tool wear with th_c compared to th_p mode at both speeds and this is also consistent with the addition of micro-lubrication. For both th_c and th_p modes, notably at high cutting speed, adding micro-lubrication significantly reduces tool wear. However, with lower cutting speeds, the impact of micro-lubrication is not that prominent. The pulsed and lubricated method (th_p-l) in milling Waspaloy is found to be the best method for high productivity as the variance in VB is not significant for high and low cutting speeds, hence milder tool wear and increase in productivity while reducing tool cost.

Tool wear generally decreases for all the Lubri-cooling modes from 120 to 80m/min, except the th_c-l mode. At high cutting speed, th_p causes more severe tool deterioration than the th_c mode, however, the addition of micro-lubrication to the pulse mode lowers the tool wear to a similar value as that of th_c-l mode. At low cutting speed, all Lubri-cooling modes yield comparable tool wear for milling Inconel 718 except for th_p -l which yielded the smallest tool wear. It can be concluded that the th_c-l and th_p-l modes of Lubri-cooling are the most effective at 120m/min and 80m/min respectively.

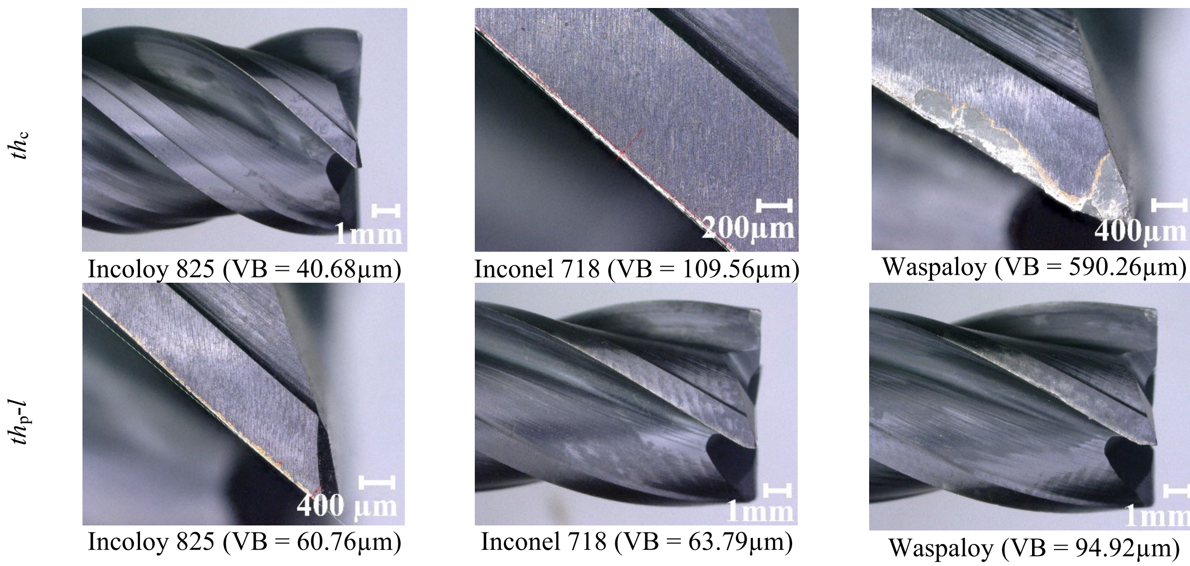
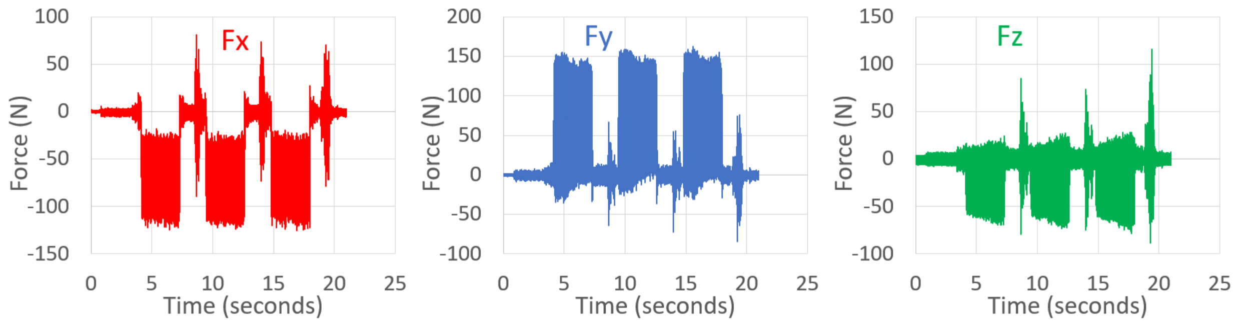


Fig. 2. Optical micrographs of the selected tools used in the milling of the three alloys.

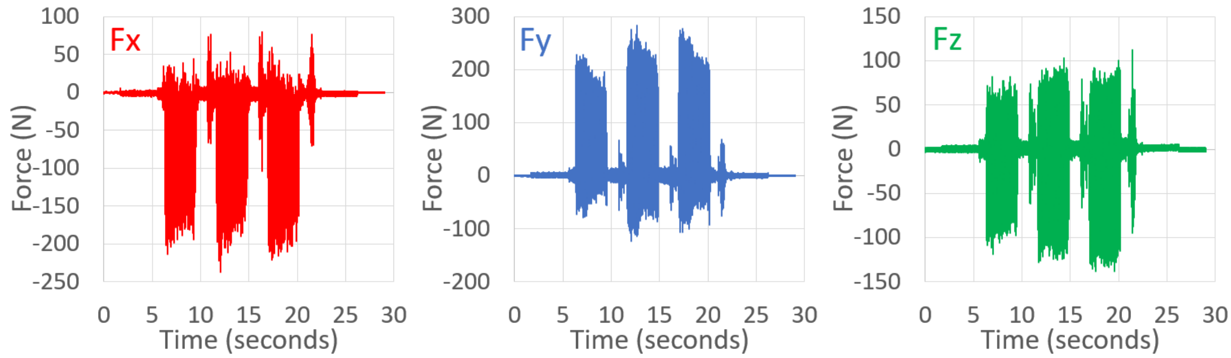
Figure 2 presents the selected optical micrographs of the cutting teeth of the cutters used in the milling of the three superalloys. The most prevalent type of tool wear that occurs while milling high-strength materials is chipping of the cutting edges. Progressive wear is also evident on the cutting edges that have not sustained severe chipping, albeit to a considerably lesser extent. All the images chosen are that of 120m/min cutting speed and are grouped into two rows of continuous CO_2 and pulsed CO_2. For Incoloy 825, chipping is not evident with the continuous mode, and the pulsed mode has yielded little indication of wear. In the case of Waspaloy, the milling cutter used at high cutting speed and under continuous mode has deteriorated severely. The pulsed mode with micro-lubrication underwent mild tool wear. Like Incoloy 825 and Waspaloy, Inconel 718 also shows tool wear sustained through chipping and progressive mechanical wear. The th_c mode shows noticeable tool wear, however, there was little tool wear observed under the th_p mode with the addition of micro-lubrication.

Cutting Forces

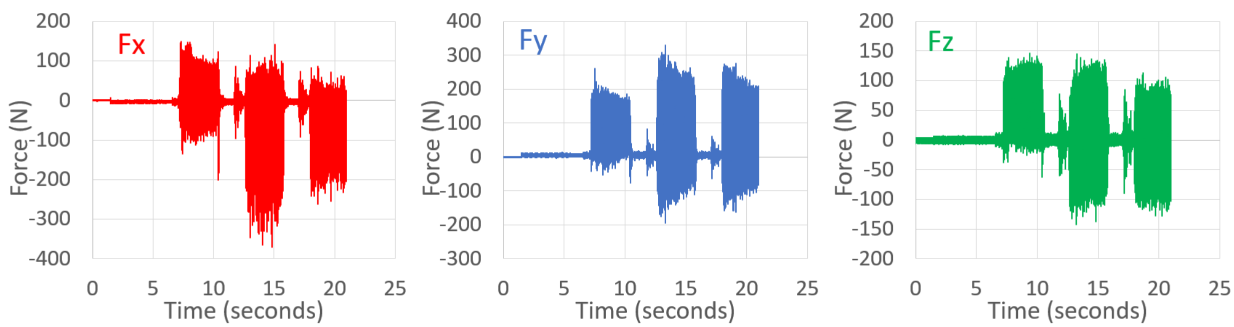
Table 3 suggests that, of the three orthogonal force components, the maximum magnitude is observed for the planar force component acting perpendicular to the feed direction (F_y), followed by the ones in the feed direction (F_x) and the axial direction (F_z), respectively. This is true for all the runs except those employing th_c at the low level of cutting speed in the milling of Waspaloy.



Incoloy 825, th_p-l (Experiment 9)



Inconel 718, th_c (Experiment 13)



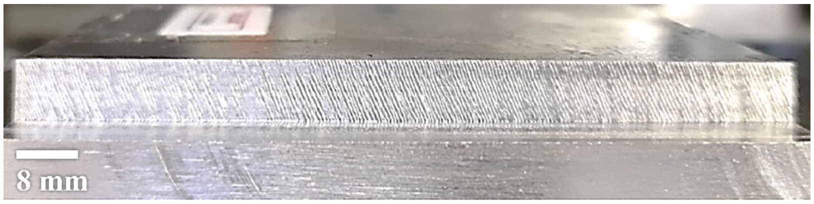
Waspaloy, dry (Experiment 21)

Fig. 3. The time-force graphs of the three orthogonal force components for the selected lubri-cooling modes of milling at the cutting speed of 120m/min

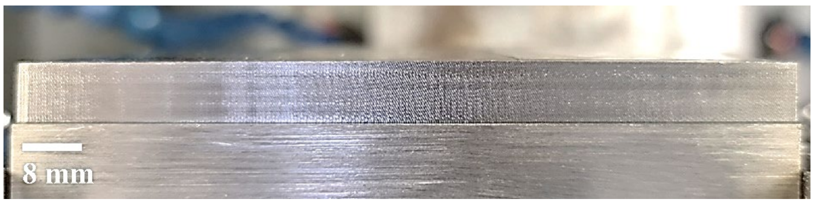
The cutting force results indicate that an increase in cutting speed results in an increase in the cutting force. The statement stands true for all three workpiece materials. Table 1 suggests that all three alloys possess contents of nickel over 40%. Thermal softening is a phenomenon that occurs when the generated process heat counteracts the strain-hardening effect. It is widely known that an increase in nickel content significantly increases work hardening, counteracting the effect of thermal softening on the workpiece material during plastic deformation. Thus, it is expected that the higher cutting speed would result in higher cutting forces.

The time-force graphs of the three orthogonal force components for the milling of Incoloy 825 (pulsed lubri-cooling), Inconel 718 (continuous cryogenic cooling), and Waspaloy (dry) carried out at the cutting speed of 120 m/min are shown in Figure 3. The shape patterns of the three force components for all the runs are more or less the same. Due to the dynamics of the side-milling process and the geometry of the tool, F_x and F_y take the higher shares of the force magnitude.

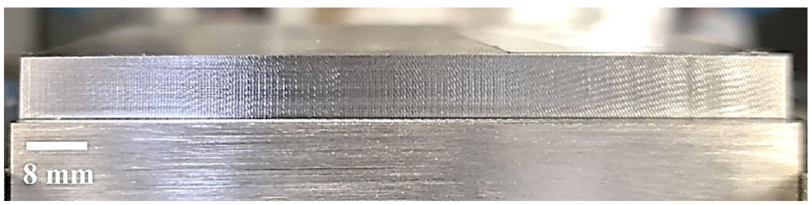
For all three alloys, the F_z graph shows that the magnitude of each of the last two passes has increased in comparison to the one before it. Furthermore, as each of the three passes goes on, the force magnitude increases. These imply that the force magnitude is uniformly increasing due to the increasing tool wear. However, the other two force component graphs show less of this behavior.



Incoloy 825, Dry, V_c = 120 m/min (R_a=3.07µm)



Inconel 718, th_c-l, V_c = 80 m/min (R_a=1.439µm)



Waspaloy, th_p-l, V_c = 80 m/min (R_a=1.457µm)

Fig. 4. The optical micrographs of the surfaces of the workpieces side-milled in selected runs of the three alloys

Work Surface Quality

The last column of Table 3 shows the average arithmetic roughness value of the surfaces generated in the 30 runs. The R_a measurements overall range between 1 and 3µm which is considerably high and can be attributed to the dynamics of the side milling process. For all three alloys, it can be deduced that the introduction of micro-lubrication to the milling process plays a major role in reducing the surface roughness and has increased the beneficial effect of the cryogenic coolant, particularly at the low cutting speed. This can be further emphasized through the observation that the finest surface generated amongst all the milling processes of the three alloys employed either continuous or pulsed cooling mode, mixed with micro-lubrication, and carried out at 80m/min. The introduction of micro-lubrication to the shear zones forms a minute film so the cutting process experiences reduced friction.

Fig. 4 presents the optical micrographs of the side-milled surfaces of the selected runs. The optical micrograph for Incoloy 835 presents the roughest of all the surfaces generated in this study. The attributed reason is the absence of any lubri-coolant and cutting at the high level of cutting speed. The processes related to the optical micrograph of Inconel 718 and Waspaloy shown in the figure were carried out at 80 m/min cutting speed using th_c-l and th_p-l, respectively. It is quite evident from the results and the micrographs that a superior surface finish is obtained through the parallel application of micro-lubrication with the cryogenic coolant no matter whether the coolant is supplied in a continuous or pulsed mode.

Summary

The presented work pitches the dry cutting approach – considered to be a sustainable way of machining a variety of engineering materials – against the throttle cryogenic medium-based lubri-cooling approach. The article has also explored the favorable outcomes of supplying the cryogenic coolant in the mode of periodic pulses. The findings of the experimental study indicate that the lowering of tool wear and cutting forces during the milling of nickel-based superalloys, such as Incoloy 825, Inconel 718, and Waspaloy can be achieved using throttling CO_2 as a cooling medium. The cryogenic coolant demonstrates favorable outcomes with reduced cutting forces and better surface finish, especially when applied in parallel with micro-lubrication. While the pulsed mode of the coolant's supply counteracts thermal gradients to yield a better surface finish and reduce cutting force in most cases, the continuous mode offers a richer cooling potential to guarantee a longer tool life.

Cutting speed is found to have little effect on tool wear when cryogenic cooling is used, so higher speeds can be used to mill the nickel-based superalloys sustainably. The addition of micro-lubrication enhances the favorable capability of the cryogenic coolant to improve the surface quality. The study suggests that the continuous mode of the coolant's supply is highly promising for productivity, yielding the lowest tool wear and the pulsed mode is suitable for reducing cutting forces and improving surface finish.

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