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Performance Assessment of Different Cooling Conditions in the Machining of Inconel 718 Alloy

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Abstract
Manufacturing sectors strive towards low-toxic, environmentally friendly machining to combat climate change. Due to its low heat conductivity, machining Inconel 718 alloy is a difficult process nowadays. The purpose of this research is to investigate the turning of Inconel 718 alloy under PVD TiAlN inserts, in two distinct environments: Dry and Atomized spray cutting fluid (ASCF). The effect of various machining performances such as Surface roughness (R_a) and Tool life (TL) analysis of Inconel 718 alloy on ecologically friendly machining were investigated. According to the results of the study, the surface roughness of the ASCF machining improved significantly, which was around 40%, when compared to its dry machining. The use of the ASCF significantly decreased the notch and abrasion wear of the tool. This was due to its various features, such as its ability to provide effective lubrication and reduce the cutting temperature.

Keywords- Inconel 718 alloy, Turning, Atomized spray cutting fluid (ASCF), Surface roughness, Tool life.

1. Introduction

Due to its excellent heat resistance, about 50% of Inconel 718 alloy is consumed in jet engine components and gas turbine blades (Yin et al., 2020). The lack of heat conductivity and strong mechanical characteristics of Inconel 718 alloy have a considerable impact on machinability throughout the manufacturing process (Korkmaz et al., 2021). When turning or milling Inconel 718 alloys, high cutting temperatures created at the workpiece-tool interface (turning or milling), cause chemical reactions with the cutting inserts. These are the primary concerns when turning or milling Inconel 718 alloys (Grzesik et al., 2018). Once the cutting speed (v_c) exceeds about 100 *m/min*, the cutting pressures and temperatures at the machined region grow rapidly, resulting in thermal softening or thermal cracking (Ezugwu et al., 1999; Zhang et al., 2018). These characteristics result in increased v_c and energy consumption, which can decrease tool life and cause major surface and subsurface flaws in machine-induced surfaces (Erden et al., 2021). Novel cooling techniques such as MQL (minimum quantity lubrication), ASCF (Atomized spray cutting fluid), ASFC with Nano fluids (Solid lubricants), cryogenic cooling, and others have been proposed as viable alternatives to enhance the machinability and tribological properties of Inconel 718 alloys (Pimenov et al., 2021). They are called "Green machining" because of the beneficial results. As the cutting fluid consumption in these cooling systems is rather modest, the environmental impacts are negligible in this case (Gupta et al., 2021). The ASCF technique is utilized in virtually all conventional machining operations, to control tool failure and optimize the machining performance surface. The ASCF concept arose from a desire to significantly enhance the surface integrity and extend tool life with minimal coolant usage in turning applications (Nath et al., 2012). Elsheikh et al. (2021) investigated the effects of the MQL method on AISI 4340 steel turning with cermet inserts utilizing Nano particles (Al_2O_3 and CuO). CuO added Nano fluids outperform Al_2O_3 added Nano fluids and enhances the surface integrity and extend tool wear, according to the researchers, due to CuO's stronger thermal properties. During the machining of pure titanium, Singh et al. (2019) examined the v_c, surface roughness (R_a), and tool wear parameters of a chilled air assisted with MQL. The usage of chilled air aided MQL and enhanced the surface quality of several hard-to-cut materials, and also lowered the risk of occupational health hazards, according to the authors. Ghosh and Rao (2019) machined Nimonic 90 super alloy with carbide inserts in comparison with cryogenic cooling and Nano-MQL techniques. This approach for minimizing tool wear was found to be cryogenic cooling. Furthermore, in connection with tool wear and surface quality, the Nano-MQL technique surpassed cryogenic treatment. Sivalingam et al. (2020) used the ASCF technique applied in machining of Inconel 718 alloy in turning application by using vegetable oil mixed with graphite and molybdenum disulphide. Hence, this research aims to reduce the environmental pollution by implementing ASCF technique. Fine atomized spray fluids are distributed throughout the tool-chip contact area, subsequently decreasing the friction, and leading to effective heat transport away from the cutting zone. The machine tool industry strives for increased productivity and efficiency, which are closely tied to optimal cutting settings. However, during machining of Inconel 718 alloy, the challenging task is to predict the optimal process parameters combination that might be difficult. This can aid towards tool wear, surface quality, and overall productivity (Debnath et al., 2014; Rajeswari and Amirthagadeswaran, 2017).

From the literature survey, it has been noticed that the effect of the graphite and MoS_2 particles on surface roughness and tool wear has not been adequately studied in the ASCF technique. The study used the ASCF technique by adding solid lubricant materials such as Molybdenum disulphide and graphite, to the turning of Inconel 718 alloy. The study aims to provide a comprehensive analysis of the turning process of the Inconel 718 utilizing a coated tool. It also explores the advantages of utilizing a coated tool in achieving the desired surface quality and tool wear under dry and ASCF machining.

2. Materials and Methods

Inconel 718 alloy, having dimensions of (Ø80 x 400 *mm*), was used for the present turning study. Table 1 shows the chemical composition of the Inconel 718 alloy. The mechanical properties of Inconel 718 alloy are: Tensile strength (1170 MPa), Yield strength (1375 MPa), Elongation (23.3 %) and Hardness (40 HRC). All of the turning experiments were carried out on DAEWOO PUMA-2000 CNC turning machining. The workpiece was machined using a PVD (TiAlN +$AlCr_2O_3$) coated carbide insert with ISO number SNMG 120408 – Sandvik. Table 2 shows all of the experimental work in detail. In this study, vegetable oil mixed with solid lubricant (graphite and molybdenum disulphide) additives is utilized for ASCF machining to explore the effect of solid lubricating cooling in the turning application. To illustrate the advantages of the ASCF technique, dry machining is also used. The producer for the preparation of solid lubricant first took 20 ml of acetone and added 0.2 wt.% of each solid additive (graphite and molybdenum disulphide). It is then blended to ensure homogenous particle dispersion. After that, a 90:10 mixtures of cutting fluid and solid lubricant is applied. The atomized nozzle consisted of two inputs: one was used to supply air pressure of 7 bar, and the other side solid lubricating flow of 30 *mL*/*h* was maintained by adjustable screw. The distance between the atomized nozzle and the cutting insert was regulated at 50 *mm* during machining. For each trial, a fresh cutting edge was employed to accurately analyze machining performance. A magnetic holder held the vibration sensor to the tool holder. Veeco NT 9300 white light interferometer non-contact type 2D surface roughness measurement was used. For each cutting condition, a TR200 portable surface roughness profilometer was employed to determine the average surface roughness (R_a). The dry and ASCF processes are depicted schematically in Figure 1.

Table 1. Chemical composition of Inconel 718 alloy.

Elements	Ni	Cr	C	Mn	Si	Co	Mo	Nb	Ti	Al	Fe
wt%	53	18	0.04	0.08	0.08	0.23	3.04	5.3	0.98	0.50	17.80

Table 2. Experimental conditions

Instruments	**Details**
Cutting speed (v_c)	50, 75 and 100 *m/min*
Feed rate (*f*)	0.1, 0.15 and 0. 2 *mm/rev*
Depth of cut (a_p)	0.4, 0.8 and 1.2*mm*
Length of cut (LoC)	40 *mm*
Optical Light Microscope	Keyence VH- Z500R magnification (500 – x 5000)

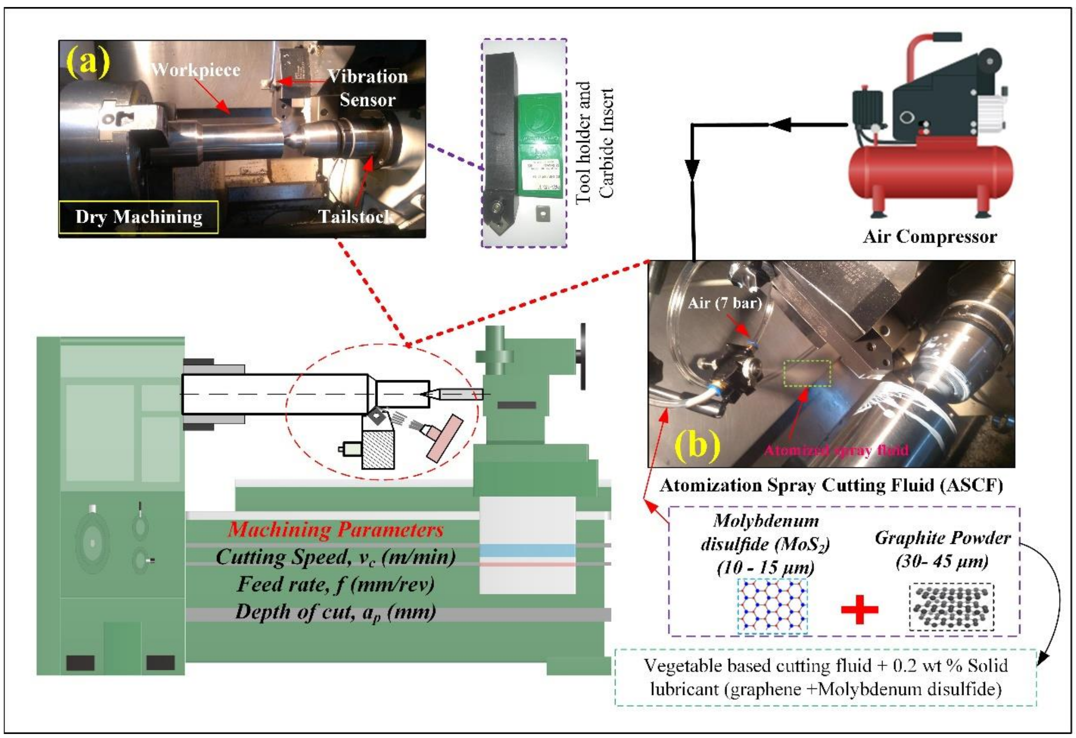


Figure 1. The schematic diagram for the dry and ASCF procedures.

3. Results and Discussions

3.1 Surface Roughness (R_a)

Dry machining roughness ranges from 0.685 to 1.291 μm, whereas ASCF machining roughness ranges from 0.698 to 0.978 μm. Increasing the *f* causes the R_a value to rise throughout the machining process. At a v_c of 50 *m/min*, *f* of 0.15 *mm*, and a_p of 0.4 *mm*, ASCF machining lowers roughness by 19 to 33 percent compared to dry machining. This is due to the presence of solid lubricants in the tool tip contact, which minimizes the amplitude of waviness on the machined surface while maintaining a uniform profile surface as viewed in 2D (Balasubramanian and Nataraj, 2019). Figure 2 shows the presence of feed marks and scratches on the surface morphology. Figure 2 depicts an optical microscopic examination of a machined surface at the ideal conditions, v_c of 50 *m*/*min*, *f* of 0.15 *mm*/*min*, and a_p of 0.4 *mm* in both dry and ASCF conditions. When compared to ASCF machining, dry machining produced more grove markings and burned marks. This is due to the presence of solid lubrication, which improves heat absorption and lowers build-up edge (BUE) development (Gupta et al., 2020; Sivalingam et al., 2021a).

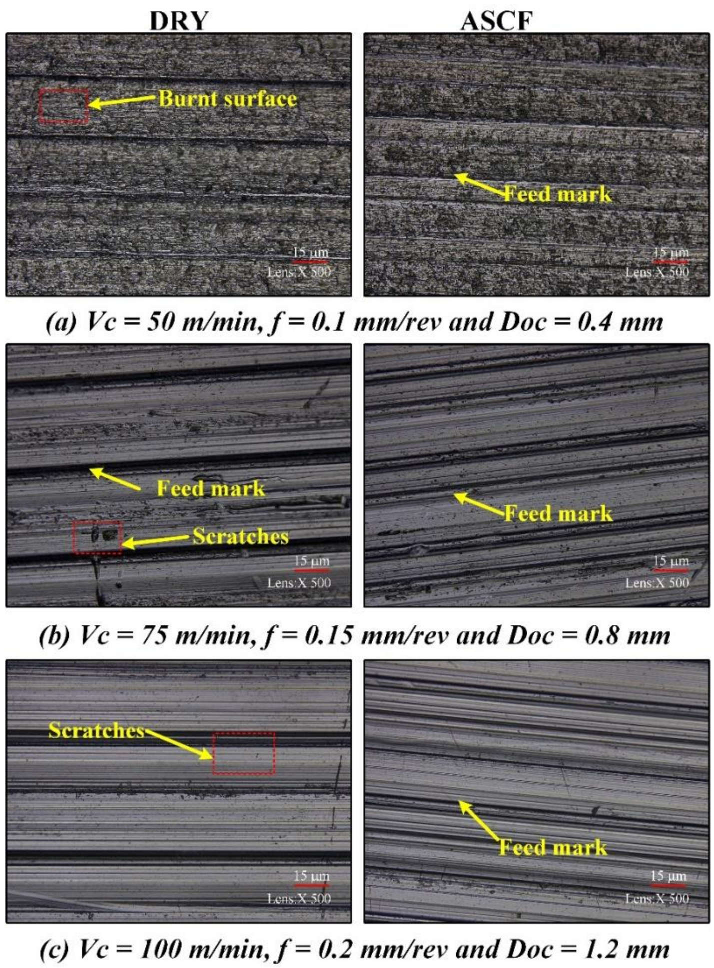


Figure 2. Optical microscopic investigation of machined surface at the optimum condition of cutting speed 50m/min, feed rate of 0.15 *mm*/*min* and depth of cut of 0.4 *mm* at both dry and ASCF condition.

When compared to the ASCF state, the machined surface has a non-uniform surface profile with a greater value of R_a. Surface roughness was a smooth, uniform surface profile without any appearance of waviness at the beginning stage of machining in both the dry and ASCF machining environments. During dry machining, chipping and BUE caused a greater value of surface roughness on the machined surface. Dry machining created more feed marks on the workpiece surface than ASCF machining because of the lower v_c and *f*. This is due to BUE being formed as a result of the long engagement of the chip with cutting inserts and the relatively large cutting temperature generated near the cutting edge at the higher feed rate (Lee et al., 2001; Siddhpura and Paurobally, 2012). Low groove markings and improved R_a on the machined surface were achieved with constructive chip breakability and decreased BUE during ASCF machining. Figure 3 depicts a 2D surface analysis of a machined surface at the ideal conditions; v_c of 50 *m*/*min*, *f* of 0.15 *mm*/*min*, and a_p of 0.4 *mm*, in both dry and ASCF conditions. The figure shows that in the dry state, there were more feed marks with non-uniform surface profiles, which is attributable to vibration build-up during the machining process. Surface roughness has a direct link to vibration buildup. The presence of solid lubricant droplets on the tooltip interface reduces the amplitude of waviness on the machined surface with a uniform profile surface, as seen in the 2D surface at the optimum condition; v_c of 50 *m*/*min*, *f* of 0.15 *mm*/*min*, and a_p of 0.4 *mm*, at both dry and ASCF condition, as seen in the images (Gupta et al., 2021; Sivalingam et al., 2021b).

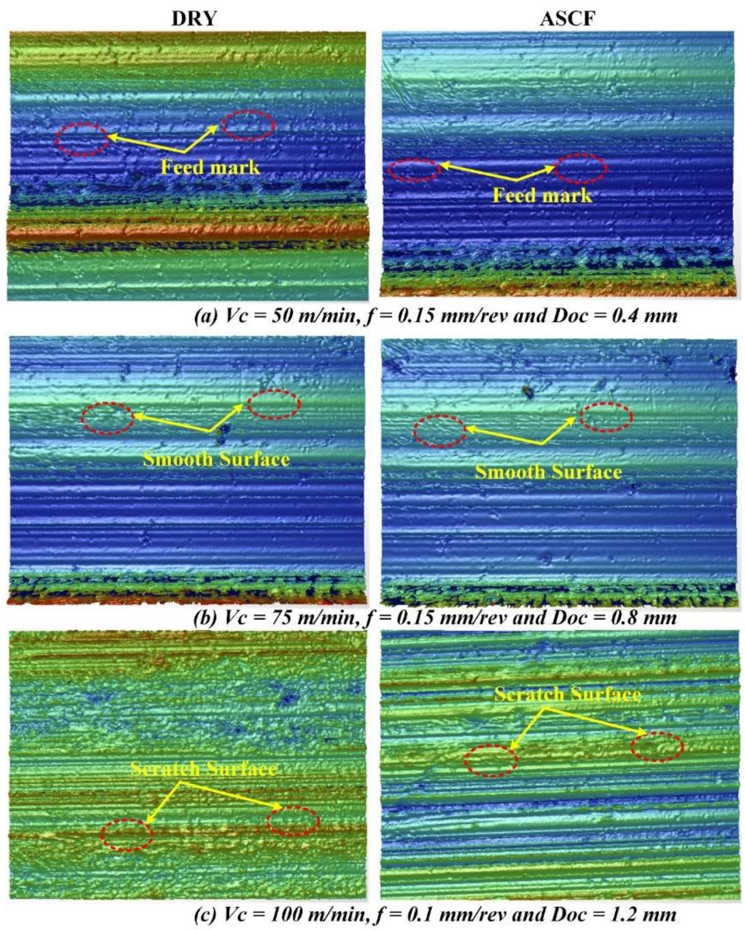
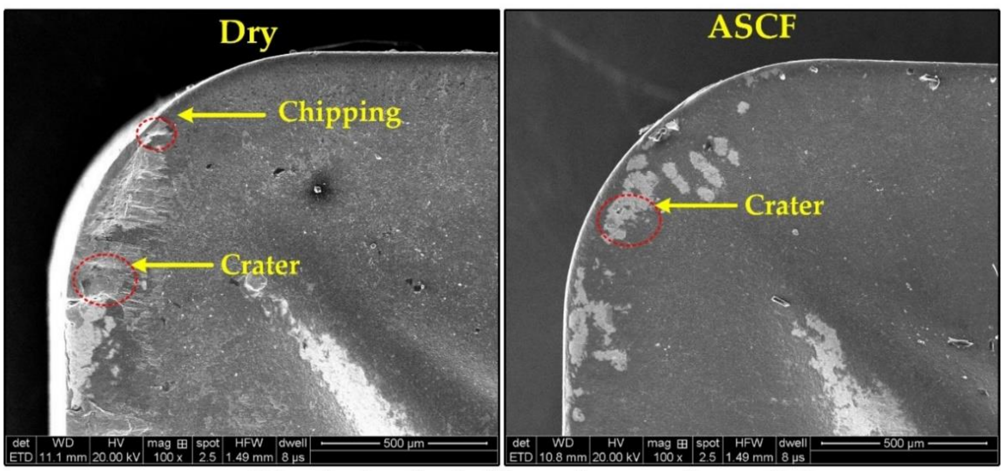


Figure 3. The 2D surface investigation of machined surface at the optimum condition of cutting speed 50 *m*/*min*, feed rate of 0.15 *mm*/*min* and depth of cut of 0.4 *mm* at both dry and ASCF condition.

3.2 Tool life (TL)

In dry machining, higher v_c causes greater plastic deformation at the tool-workpiece contact, resulting in shorter tool life. The presence of small spray droplets of solid lubricants during machining in ASCF minimizes the coefficient of friction along the workpiece and the cutting edge, reducing cutting edge sharpness during machining at high temperatures. In contrast to dry machining conditions, ASCF machining extends tool life by up to 40%–60%. Figure 4 illustrates the SEM analysis of tool wear at the optimal conditions of 50 *m*/*min* cutting speed, 0.15 *mm*/*min* feed rate, and 0.4 *mm* depth of cut in both dry and ASCF conditions. Craters and chipping were evident on the tool surface due to tool wear in both dry and ASCF machining environments. In the dry condition, more craters and chipping were found on the surface due to the tool and work interface at higher speeds, whereas in the ASCF condition, fewer craters and chipping were found on the surface due to the presence of solid lubricants during the machining process, resulting in a lower tool wear rate (Danish et al., 2022; Gupta et al., 2022). During the turning of the workpiece in both dry and ASCF conditions, the adhesive chipping layer was visible on the rake surface of the tool (Bhatt et al., 2010; Chavan et al., 2019). When opposed to dry machining, ASCF displays less crater wear and chippings due to the presence of high thermal stress and a high strain hardening rate during the machining process. The finding is also in line with that of An et al. (2020) and Pal et al. (2020). Solid lubricants provide a cooling effect, which lowers the cutting tool temperature at the interface zone and increases tool life. ASCF machining demonstrates less substantial fracture and diffusion area, and the damage is significantly smaller owing to solid lubrication, which minimizes the heat created during the machining process and results in longer tool life (Danish et al., 2021).



$v_c = 50\ m/min,\ f = 0.15\ mm/rev\ and\ a_p = 0.4\ mm$

Figure 4. SEM view of rake face under dry and ASCF condition.

4. Conclusion

The study evaluated various aspects of dry and atomized spray cutting fluid (ASCF) in turning Inconel 718 alloy using coated carbide inserts. In contrast to dry machining, ASCF machining improved surface roughness by 17%–40%. ASCF machining provides effective lubrication between the chip-tool interfaces as well as reduces the cutting temperature in the cutting zone. Under dry and ASCF machining processes, carbide inserts are most likely to wear at the crater and flank areas. The abrasion and chip wear of the tools were significantly improved by ASCF spray coolant due to the less accumulation of chips when compared to dry machining. ASCF can significantly alter flank and crater wear conditions. Additionally, it can extend the life of the tool in comparison with dry machining. This is because of a solid lubricant that absorbs heat quickly during the machining process, which minimizes friction and heat at the work piece-tool interface, lowering the cutting temperature and increasing tool life.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments
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