Studying the effects of using liquid carbon dioxide and soap water in grinding Inconel 718

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Abstract. Inconel used in industrial applications is usually subjected to extreme conditions of heat and pressure. Desirable material properties like high hardness and high compressive residual stresses are not always ensured by using conventional cooling methods, while grinding such alloys. However, with increasing hardness, cutting forces and energy requirement also increase naturally. Hence, a balance has to be obtained between the two. This paper uses soap water and liquid carbon dioxide as the grinding fluid during surface grinding of Inconel 718, a Nickel based alloy. A novel method to apply both soap water and liquid carbon dioxide is employed here. It is observed that minimum grinding force and high surface hardness are achieved using the soap water-liquid CO₂ combination. Furthermore, ground surface quality is found to improve using liquid carbon dioxide.

Keywords: Grinding; lubrication; soap water; liquid carbon dioxide; Inconel; surface quality; hardness

1. INTRODUCTION
Inconel is a family of Nickel Chromium alloys, developed in the late 1940’s by Wiggins Alloys, England [1]. Owing to superior physical properties such as high temperature and corrosion resistance, coupled with superior creep rupture strength, these alloys are termed as “superalloys”. They are extensively used in the aircraft industry, heat exchanger industry, power plant industries etc. The most commonly used superalloy is Inconel 718, accounting for almost half of the total wrought Nickel based alloy production, and almost one-fourth of the total cast Nickel based production [2]. Used for temperatures around 704°C, Inconel 718 is used to make gas turbine blades, rocket motors, parts of jet engines, pump bodies and parts, cryogenic storage tanks etc. These are all high temperature applications, and so high material hardness, high surface finish and close dimensional tolerances are desirable properties of the part manufactured. Grinding is the primary step to achieve these demands, so grinding of Inconel is a topic of general interest around the world. However, problems associated with grinding increase manifold owing to low thermal diffusivity, rapid work hardening and increased tool affinity of the alloy [3].

To overcome these problems, various cooling and lubrication methods, such as flood cooling [4], [5], jet cooling [6], Minimum Quantity Lubrication (MQL) [7], and cryogenic cooling [8] are used. However, they are losing their importance due to high procurement and disposal costs, negative health impacts, reduced efficiency due to the stiff air layer around the grinding wheel [9], [10].
The two most common industrial gas-based coolants are liquid nitrogen and liquid carbon dioxide. Reduction in surface roughness, cutting temperature and surface defects with liquid N\textsubscript{2} cooling were reported by Shokrani et al. [11] and Ahmed et al. [12]. Compared to liquid N\textsubscript{2}, cryogenic CO\textsubscript{2} is cheaper and also available in vast amount [13]. Cordes et al. [14] used liquid CO\textsubscript{2} during milling of stainless steel. Low tool wear and a high material removal rate were reported, when compared to dry milling. Also, chip adherence was visibly suppressed.

As a low-cost easily available lubricant, soap water is an efficient choice in this regard, as past researchers have proved. Significant reductions in grinding force, favourable chip formation and smooth workpiece surface were seen [15], [16], [17]. Numerous studies have been made on the effect of machining conditions on cutting forces, surface characteristics. However, to the author’s best knowledge, there is a gap in literature on the effects of using a coolant combined with a lubricant during grinding a difficult-to-machine alloy, such as Inconel 718. This paper presents a novel approach to incorporate conventional soap water and liquid CO\textsubscript{2} as a lubricant-coolant combination and study forces generated, workpiece quality and surface roughness, and workpiece hardness during grinding of Inconel 718.

2. EXPERIMENTAL INVESTIGATIONS
Surface grinding of Inconel 718 was performed on a horizontal axis surface grinding machine. An alumina grinding wheel was used, while rectangular flats of Inconel 718 were used as the workpiece material. Chemical composition of the Inconel alloy sample, obtained by spectrometer analysis, is given in Table 1.

| Ni  | Fe  | Cr  | Nb  | Mo  | Ti  | Co  | Al  | Others |
|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| 54.9| 18.6| 17.1| 4.6 | 2.8 | 0.8 | 0.6 | 0.3 | 0.3    |

20 upgrinding passes with 10 µm depth of cut (infeed) were given for each set of experiments. To remove wheel loading, dressing of the wheel was done after each experiment with a 0.5 carat diamond tipped dressing tool. Force values were measured by a Sushma, Bengaluru, India made strain gauge type dynamometer. Surface roughness was measured by a portable surface roughness tester of Mitutoyo, Japan make. The complete equipment details along with process parameters are listed in Table 2.

| Grinding machine | Horizontal axis surface grinding machine, HMT Praga Division India |
|------------------|---------------------------------------------------------------|
| Grinding wheel   | Alumina disc type, Make: Carborundum Universal |
|                  | Dimension: \( \phi \)200mm x \( \phi \)31.75mm x 20mm |
|                  | Specification: AA60K5V8 |
| Workpiece        | Inconel 718, Dimension: 120mm x 60mm x 6mm |
|                  | Hardness: 82 HRB |
| Wheel velocity   | 30 m/s |
| Depth of cut     | 10 µm |
| Table speed      | 14 m/min |
| Fluid and coolant| 5 % soap solution, liquid CO\textsubscript{2} |
| Process parameters| Environmental conditions: |
|                  | • Dry |
|                  | • Using liquid CO\textsubscript{2} coolant |
|                  | • Using a combination of liquid CO\textsubscript{2} and soap water |

The various grinding conditions are described in the following with appropriate diagrams:

2.1. Dry grinding
Dry grinding of Inconel 718 was performed for 20 up grinding passes.

2.2. Grinding using liquid CO₂
Food-grade liquid CO₂ was used as the coolant in this study. A steel nozzle of 3.25 mm diameter supplied the gas in the form of a jet, at a temperature of -26°C. The cylinder pressure was fixed at 70 kgf/cm² while the exit pressure was 3 kgf/cm². Figure 1(a) represents the setup for grinding with liquid CO₂.

2.3. Grinding using liquid CO₂ and soap water
A combination of liquid CO₂ coolant (at -26 °C) and a jet of soap water (1:20 by volume), supplied by a nozzle of 1.23 mm, was used. A micro-sized pump, consuming only 10 W power, was used to deliver the soap water at the grinding zone. The used lubricant is filtered and drained into the same tank wherefrom the micro-pump is operating, ensuring automatic recycling of the grinding fluid. Figure 1(b) shows the setup used in this study.

![image](image.png)

**Figure 1(a), (b).** Experimental setup (a) Using liquid CO₂ and (b) using liquid CO₂ assisted cooling with soap water

Surface roughness values (Rₐ) were measured by portable surface roughness tester in the transverse direction. Measurements were taken at five different locations along the length of the workpiece and average values were calculated. A stereo-microscope was used to study the chip forms and the ground workpiece surface.

3. RESULTS AND DISCUSSION
The tangential force and normal force, measured by a strain gauge type dynamometer, have been plotted for each grinding pass, as shown in figure 2 and figure 3 respectively. Initially, tangential forces under dry grinding are low (compared to other cooling conditions), more or less till the 9th pass, after which it achieves a high value. The curve is smooth and does not rise or fall abruptly, indicating no intense wheel loading or auto-sharpening. Grinding with combined liquid CO₂ and soap water jet also reported less tangential force, till the 4th pass, after which it rises sharply at the 5th pass and again falls, continuing this trend for almost the entire experiment. This may be due to intense wheel loading and consequent auto-sharpening of the wheel. The force curve is seen to be on the lower side, signifying the average grinding force (tangential) is the lowest. This may be due to the good lubricating property of soap water, enabling better lubrication between the workpiece and the abrasive grains. High tangential and normal grinding forces were seen in case of grinding using only liquid CO₂. Inconel 718 workpiece might have got hardened due to application of low temperature CO₂ gas, as evident from the measured hardness values given in figure 4.
Figure 2. Variation of tangential forces with grinding passes

Figure 3. Variation of normal forces with grinding passes

Figure 4(a)-(c). Surface texture when grinding Inconel 718 under (a) dry, (b) using liquid CO$_2$, (c) using liquid CO$_2$ and soap water

As evident from figure 4(a), few dark spots are seen, which may be caused by removal of some material from the work surface. This occurred probably due to high grinding temperature and high friction. Some deep streak marks are also observed on the surface which indicates major mode of material removal to be shearing. Amount of streak marks obtained is quite negligible when grinding Inconel 718 with liquid CO$_2$ coolant as seen in figure 4(b). This is due to increased hardness of the workpiece at a low temperature which offers more resistance to scratching or penetration by the grits. Figure 4(c) shows surface morphology when grinding Inconel 718 with liquid CO$_2$ assisted microjet soap water. The surface, apparently, is found to be free from any cracks or defects. This may be due to
low grinding temperature achieved by the low temperature liquid CO\textsubscript{2} coolant and the microjet of soap water which may have reduced friction and heat generation and related thermal defects.

Average surface roughness values (R\textsubscript{a}) have been measured at five different locations on the ground surface of the workpiece in transverse direction. Their average values are presented in Table 3.

| Table 3. Average surface roughness values | Dry | Liquid CO\textsubscript{2} | Liquid CO\textsubscript{2} assisted cooling with soap water |
|------------------------------------------|-----|---------------------------|----------------------------------------------------------|
| R\textsubscript{a} (\mu m)               | 1.18| 1.02                      | 0.9                                                      |

The highest surface roughness occurred in case of dry grinding, due to streak marks due to streak marks occurring by shearing action on the ground workpiece surface. Absence of any lubrication or coolant results in high heat accumulation in the wheel- workpiece contact zone. Consequently, thermal expansion and outward surface movement of the workpiece occurs, due to which a poor surface is generated [18]. Reduction in almost 24\% R\textsubscript{a} was achieved by the liquid CO\textsubscript{2} assisted soap water microjet. This may be due to better heat dissipation by the low temperature coolant, which reduced grinding temperature and surface defects.

Microhardness of the ground workpiece was measured using the Vickers microhardness tester. A square base pyramid shaped diamond indenter was used, subjected to a load of 500 gm, for a dwell time of 10 s. For each condition, microhardness was measured at five different locations on the ground surface of the workpiece. Average values of them are shown in figure 5. The error bars shown indicate the difference between the maximum and minimum microhardness measured. This variation may be due to microstructural differences of the sample.

The bar chart shows that with every condition, hardness of the workpiece increases. However, using the liquid CO\textsubscript{2} coolant, increase in hardness is almost 10\% compared to that of dry grinding. This is likely due to a higher rate of cooling, which decreased the amount of grain recovery. Actually, a combination of both lower thermal softening effect along with increased grain refinement leads to a higher surface hardness in the samples [19]. Using soap water along with liquid CO\textsubscript{2} results in almost the same hardness (increased by only 0.83\%). It is generally expected that a high surface hardness will lead to increased grinding force requirement, but this was surprisingly, not the case here. Forces obtained were on the whole low, probably due to good lubricating ability of the soap water delivered as a microjet, penetrating deep inside the grinding zone.
4. CONCLUSION
This work highlights an innovative technique to combine soap water and low temperature liquid carbon dioxide while grinding Inconel 718, an important material used in high temperature applications. Results obtained from this experiment show that using a liquid CO$_2$ assisted microjet of soap water, increases hardness and reduces force requirements on the whole, and at the same time reduces workpiece surface roughness and surface defects thereby achieving acceptable surface quality. The arrangement is simple, cost-effective and environment-friendly, facilitating the need for implementing a similar technique in industrial applications.

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