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Current summary of surface integrity when machining Inconel 718 under different cooling and lubrication strategies

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ABSTRACT

Cutting tool creates friction, and the materials go through the deformation phase that leads to the generation of heat during machining process. Inconel is a superior material that is broadly used in the aerospace industry to make turbine casings, discs, and engine shafts. The greater challenge which will be faced when the process takes place is due to the relatively low conductivity of heat with 11.4 W/m.K. Therefore, the heat generated will focus in the vicinity of the cutting area which creates trouble for heat dissipation and may lead to destruction of surface integrity. To avoid work hardening of the machined surface, a few strategies of cooling and lubrication had been proposed. This paper aims to review the best method of cooling and lubricating on difficult-to-cut materials. This study is crucially essential to improve the machining performance regarding surface integrity as the surface condition of materials is a major concern in aerospace application.

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1.0 INTRODUCTION

Traditional or conventional machining is a process of material removal from a workpiece by producing swarf or chips (Shokrani et al., 2012). Sharp-edged cutting tools are employed in the machining tools such as lathes, milling machines and drill presses to eliminate material and obtain the desired geometry. Turning, boring, drilling, milling, broaching, sawing and others are examples of conventional machining (Liew et al., 2017). In the past 20 years, milling performance has significantly increased in the automotive, aerospace, energy, petrochemical and biomedical industries, and it continues to grow at a rapid pace (Khatri and Jahan, 2018).

Inconel 718 which is also known as Heat Resistant Super Alloy (HRSA) from nickel-chromium groups is used in almost 50% of aerospace components. This nickel alloy consists of Iron, niobium, aluminium, molybdenum, titanium, cobalt, carbon, manganese and silicon (D'Addona et al., 2017). Inconel 718 possesses unique characteristics like high strength at elevated temperatures, high hardness as well as brilliant wear and corrosion resistance. This characteristic has made Inconel 718 become a preferred material for extreme operational environments (Haron et al., 2019; Iturbe et al., 2016; Shokrani et al., 2017). However, this superalloy has poor thermal properties which lead to high heat temperature, high chemical affinity that leads to diffusion wear and existence of carbide particles makes it hard to cut at high speed conditions (Kamata and Obikawa, 2007; Tonday and Tigga, 2019; Welling, 2014).

During machining, most of the mechanical energy used to deform this material is converted to heat. Figure 1 illustrates the tool-chip-workpiece interface where heat generation occurs. On account of its low thermal conductivity, the heat generated is focused at the vicinity of the cutting zone which produces negative impact on the surface quality (Ando and Sumiya, 2020; Rifat et al., 2017). As an alternative, cutting fluid is applied during machining to dissipate the heat generated in order to avoid or reduce the thermal damage on the workpiece (Bakar et al., 2020). On top of that, cutting fluid may assist in flushing the chips from the cutting area, curb chemical diffusion, lubricate the tool-workpiece interfaces and serve as surface preservation from corrosion (Rubio et al., 2015). A few strategies have been proposed to supply the cutting fluid such as flood coolant, high-pressure coolant (HPC), minimum quantity lubrication (MQL), cryogenic and chilled air. The aim of this study is to focus on the methods of cooling and lubrication conditions during machining and their impact on surface roughness.

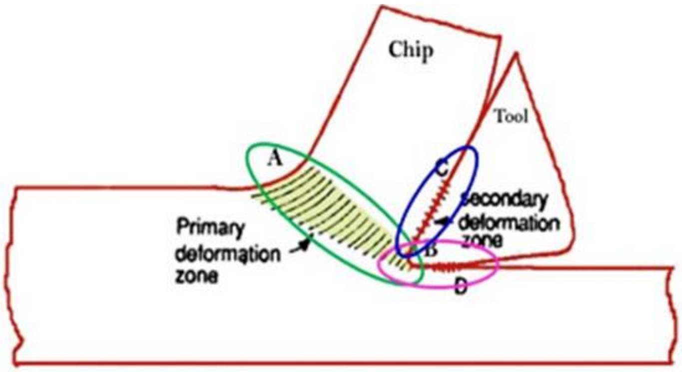


Figure 1: Sources of heat generation in metal cutting (PradeepKumar et al., 2015).

2.0 EXPERIMENTAL PROCEDURE

2.1 Flood Coolant

Flood coolant or wet machining is a conventional method that is widely used in the metalworking processes to subside the generation of heat. The cutting fluid is supplied to the cutting interface at a large amount of volume, 1000 L/min (Kasim et al., 2013). In real practice, only low volume of cutting fluid is utilized in the cooling and lubrication process (Ko et al., 2021). This is due to its poor penetration ability which leads to heat accumulation and temperature rise, hence flood coolant has low cooling capacity (Shokrani et al., 2012).

Moreover, the costs related to flood cooling take up to 16-20% of the total production cost in the manufacturing industries (Setti et al., 2015). Large amount of coolant had caused alarm to health and safety of the operator and environment. According to the National Institute for Occupational Safety and Health (NIOSH), metalworking fluids are exposed to approximately 1.2 million workers employed in metal industries each year.

During machining operation, the application of cutting fluids creates an airborne mist. Past medical evidence stated that workers exposed to cutting fluid mist are more exposed to risk of respiratory complications and various forms of cancer (Adler et al., 2006; Lee et al., 2010). The handling and disposal methods are also impractical as it does not only needs additional expense but also more effort due to the strict environmental protection policies (Debnath et al., 2014). All these issues force the researchers to find alternative methods to overcome this problem without compromising its functionality.

2.2 High Pressure Coolant

High pressure coolant (HPC) has reported to increase productivity compared to conventional coolant (Ezugwu et al., 2005). HPC is almost the same as conventional flooded technique but with different applications where high pressure is used to pump highly pressurized water streams. The jet is directly shot to the rake face of the tool and the workpiece or between tool rake face and chip formed. By performing the above method, the fluid is allowed to perform its lubricant and cooling functions more effectively as the method assured that the cutting fluid jetted as near as possible to the critical point on the secondary shear zone (Machado and Wallbank, 1994). The pressure supply is in the range of 5.5 to 35 MPa. Cutting fluid with high pressure is delivered via a special nozzle to the cutting zone, hence successfully increases the rate of heat removal. This method acts as chip breaker that minimizes the contact time between the tool and the chip (Kalpakjian et al., 2014).

2.3 Minimum Quantity Lubrication (MQL)

Minimum quantity lubrication (MQL), also known as near dry machining (NDM), emerged in the 1990s as a competent method to replace flood coolant. MQL machining uses a small quantity of cutting fluid with 50-100 ml/h and 5-10 bar of compressed air to the cutting area (Ezugwu, 2005). This technique is practical in terms of sustainable production following the ISO 14000 standard as it consumes less lubricant. The disposal issue could be eliminated through this method since the amount of fluid used is very little. The cutting fluid will be released in the form of mist or aerosol (mixture of air and oil) through a nozzle as a coolant and lubrication for the cutting area by reducing the friction between the chip/tool and tool/workpiece interfaces, hence further reduces the temperature at the cutting zone (Tawakoli et al., 2009). It also helps to blast away the chips. MQL using vegetable oil as base fluid is renewable, biodegradable and does not pose any health risk or environmental pollution, thus it is much more economical compared to mineral-oil cutting fluid (Okafor, 2020). Studies by Kishawy et al. (2005) and Weinert et al. (2004) mentioned that MQL improves machining performances in drilling, milling and turning.

2.4 Cryogenic

Cryogenic has been introduced over a century ago to produce a low temperature environment. The cryogenic term starts at temperature below 0˚C (Abele and Schramm, 2008; De Chiffre et al., 2007). Liquid nitrogen (LN_2) is the most common cryogenic liquid used in cryogenic machining as it is odorless, colorless, tasteless, harmless, incombustible and non-corrosive (Aramcharoen and Chuan, 2014). Other liquefied gases like CO_2, helium, hydrogen, neon, oxygen, argon and nitrogen are also used as an alternative to conventional coolant (Dhar et al., 2006; Ibrahim and Ahmad, 2018). The coolant is fed at subzero temperature into the cutting zone to lower the heat generated during cutting. The gas will evaporate into the atmosphere; thus, the cutting tool, workpiece, swarf, and machining area will not be contaminated by residues. Coolant disposal is no longer an issue, and it does not cause any greenhouse effect, which is advantageous for health and environment (Okafor, 2020). The application of cryogenic technique to the cutting zone at subzero temperature is proven to improve surface finish by 88% while 23% of reduction in cutting force when compared to dry machining (Musfirah at al., 2017).

2.5 Chilled Air

Air can be easily accessed in almost all places. In order to produce chilled air, vortex tube is utilized. Vortex tube (Figure 2) is used to jet chilled air at the interface of a cutting tool and workpiece which reduces the temperature of the workpiece. The device functions to isolate the hot and cold air within the tangentially flowed compressed air into the vortex chamber through the inlet nozzle (Singh et al., 2019). The exited cool air temperature is less than 20˚C (Ko et al., 1999). Rubio et al., (2015) stated that at high working pressure, air is an efficient fluid for cooling as the convection coefficient of air increases at this working condition. The chilled air helps to avoid work hardening as it maintains the surface hardness closer to the as-received material. This cooling technique is described as the most hygienic and most environmentally friendly cooling method in machining operation (Elshwain and Redzuan, 2014).

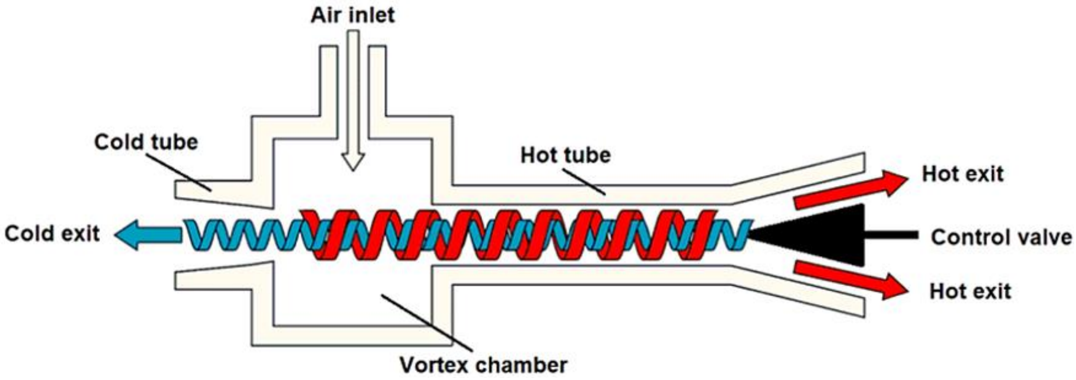


Figure 2: Vortex tube scheme (Clemente et al., 2017).

3.0 RESULTS AND DISCUSSION

Surface roughness is one of the most crucial elements in surface integrity which is considered as a product quality index to measure the surface finish of a product (Choudhury and El-Baradie, 1997; Kasim et al., 2019). Due to the need for accuracy, fatigue strength, and tribological properties of mechanical products, the demands for a high surface finish output are soaring (Lin et al., 2020). In aerospace industries, the components are put through critical stress, high temperature and hostile environments. Therefore, a great surface quality needs to be achieved to avoid stress, corrosion and cracking on the surface components (Devillez et al., 2011). The primary cause of high surface roughness is high temperature during nickel alloy machining. Therefore, machining condition is one of the factors that influence surface quality and dimensional accuracy of a product. Among all the methods of cooling and lubrication conditions, MQL and cryogenic are extensively applied in machining. HPC is a costly method due to the high volume of lubricants and improper disposal methods, may cause harmful effects to the environment.

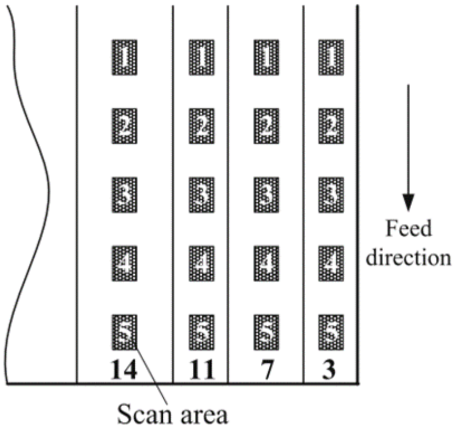


Figure 3: Positions of surface measurement using white light interferometer (Jiang et al., 2010).

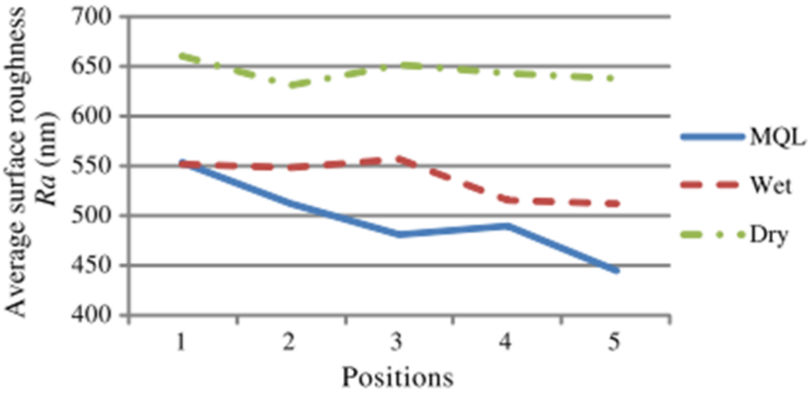


Figure 4: The average Ra from different position of measurement and cooling/lubrication strategies (Jiang et al., 2010).

Jiang et al. (2010) carried out a research of surface roughness (Figure 3) in end milling using uncoated cutting tools under dry, wet and MQL. The result from Figure 4 shows MQL has the lowest value of surface roughness compared to dry and wet machining conditions. In the experiment performed by de Oliveira et al. (2020) shows that the surface improved when high flow rate of 270ml/h is applied compared to 40.7 ml/h and 0 ml/h. Table 1 contains the measurement of surface roughness for three different lubrication conditions, while Figure 5 illustrates the surface of slot milling at 270 ml/h. At flow rate of 40.7 ml/h, the feed marks and burrs appearance increase which affect the surface quality of Inconel 718. This proves that MQL increases surface quality during machining as the oil particles penetrate at the tool-workpiece interface, thus friction is reduced (Aslantas et al., 2016).

Table 1: Surface roughness of different lubrication conditions (de Oliveira et al., 2020).

Lubrication	**Surface Roughness, Ra (μm)**
Dry	0.23 ± 0.0153
Low rate (40.7 ml/h)	0.16 ± 0.0267
High rate (270.0 ml/h)	0.14 ± 0.0056

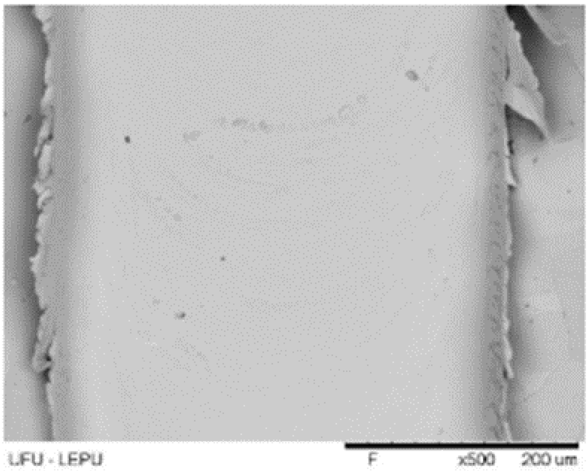
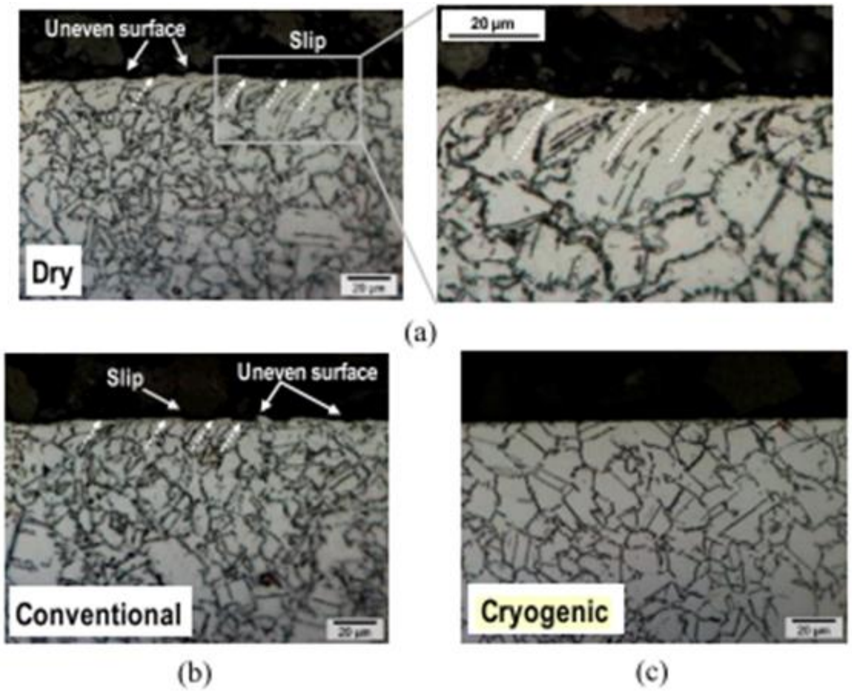


Figure 5: Surface of slot mill at 270 ml/h flow rate (de Oliveira et al., 2020).

Another approach is cryogenic cooling which aids to reduce heat and increase the rate of heat distribution during machining of difficult-to-cut materials (Aramcharoen and Chuan, 2014). The influence of cryogenic machining for Inconel 718 was studied by Shokrani et al. (2012). Surface roughness has drastically lessen, from 0.21μm to 0.14μm compared to dry machining, resulting in more than 33% reduction of surface roughness. Aramcharoen and Chuan (2014) investigated cryogenic milling compared to conventional cooling and dry machining. In cryogenic cooling, plastic deformation and surface defects (Figure 6) of Inconel 718 are less observed compared to the other two machining conditions. This is due to the efficient penetration of liquid nitrogen at the cutting zone that helps to lower the temperature during machining.



(a)

(b)

(c)

Figure 6: Surface finish of (a) dry (b) flood coolant and (c) cryogenic conditions (Aramcharoen and Chuan, 2014).

From the literature, MQL and cryogenic proved their effective cooling and lubrication functions during machining. Therefore, these two techniques have been combined and the results showed improvement in machining. Pusavec et al. (2011) through their work studied the characteristics of nickel superalloy in turning process under dry cutting, minimum quantity lubrication, cryogenic and combination of Cryo+MQL. The results found CryoMQL provides the lowest value as almost 40% reduction of Ra was achieved at cutting speed, vc =60m/min, feed rate, fz= 0.05 mm/rev, and depth of cut, ap = 0.63mm. Shokrani et al. (2017) performed a set of scientific procedures on end milling by using coated solid carbide tools. They investigated surface roughness of nickel-based alloy under MQL, cryogenic and hybrid CryoMQL. When the results are being compared, cryoMQL is proven to boost the machinability of alloy 718 as the result on tool life shows that it almost doubles the initial record and the surface roughness improved by 18% from MQL environment.

Bagherzadeh and Budak (2018) reported when machining under simultaneous cooling and lubrication conditions of liquid carbon dioxide and MQL, the surface roughness is remarkably lower compared to cryogenic. This can be proved from Figure 7 where the welded chips, irregular feed lines and small cracks are absent from the machined surface. The combination between cryogenic and MQL increases the machinability, but the cryogenic cooling is costly and has a complicated delivery system (Ramesh et al., 2003; Sterle et al., 2020). Therefore, chilled air is used to substitute the cryogenic gas, since air is a natural resource, thus cheaper to produced compared to other coolants. The cold air guns or vortex tube could be utilized to achieve temperatures as low as -34°C to help lower the temperature at the cutting area. As a result, machining performances like surface finish are improved.

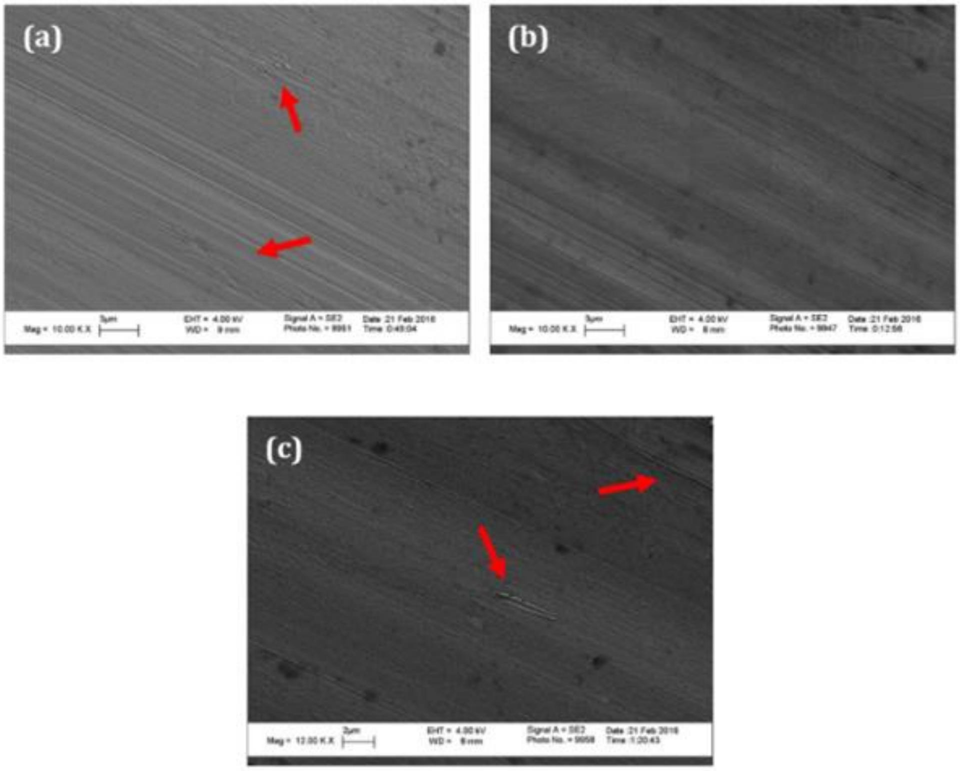


Figure 7: SEM images of turning Inconel 718 under a) CO_2+MQL, b) CMQL and c) CO_2 (Bagherzadeh and Budak, 2018).

Mehta et al. (2018) investigated Inconel 718 in a turning operation to evaluate the surface roughness under dry, MQL, cold air + MQL, cryogenic, cryogenic + MQL. The result shows satisfactory surface roughness values under combination of MQL and cold air where 85% reduction compared to dry and 1% increment compared to cryoMQL and cryogenic conditions. Su et al. (2007) stated that machining Inconel 718 under the application of cooling air (-20˚C) and minimum quantity lubrication (90 ml/h) (CAMQL) resulted in drastic reduction of surface roughness as portrayed from Figure 8. The improvement of machined surfaces is credited to the reduction of tool nose wear under cooling air and CAMQL cutting conditions.

4.0 CONCLUSIONS

this paper, different methods of cooling/lubrication conditions were discussed. Cutting fluid helps to reduce heat generation during machining. However, large volumes of cutting fluid cause harmful effects to worker's health and environment. Alternative methods such as MQL, cryogenic and chilled air were applied in machining. The study reflected that all the methods help in improving surface roughness of Inconel 718 in machining operations especially when two methods are combined. The combination method of MQL and cryogenic/chilled air provides efficient cooling and lubrication properties in reducing temperature generated during machining that leads to improvement of surface quality. To conclude, MQL and chilled air produce low surface roughness, more cost effective and better sustainability.

Challenge in milling of Inconel 718 is to machine under sustainable environment especially in aerospace industries as the material properties will always improve every year due to the advanced processing. Therefore, the cooling and lubrication strategies need to evolve with the materials development to achieve better surface quality during machining process.

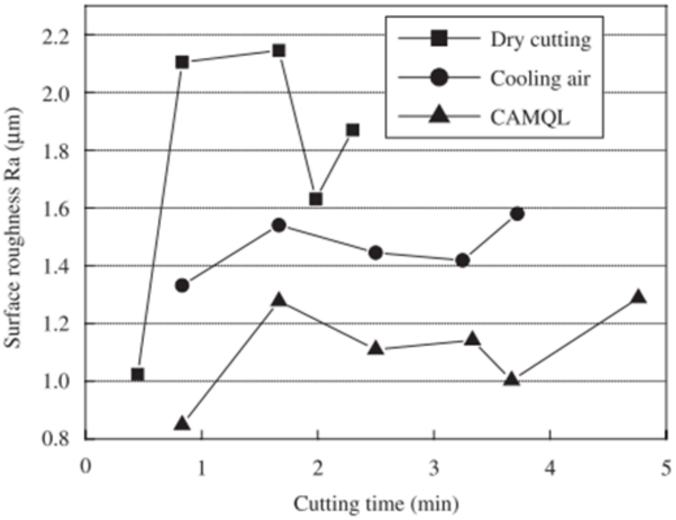


Figure 8: Surface roughness of Inconel 718 under various cooling/lubrication conditions (Su et al., 2007).

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