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Comparative Analysis of Surface Roughness and Tool Wear under Dry, MQL, and Cryogenic Machining Conditions in Invar 36 Turning Operations

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Abstract

Invar 36 alloy is known for its exceptional stability, presents challenges due to its tendency to heat up while machining which can result in deformation and decreased precision. This investigation presents a comparative study of surface roughness and tool wear performance during dry, Minimum Quantity Lubrication (MQL) (using canola oil) and cryogenic (LN2) machining of Invar 36 alloy. The changes in surface roughness and tool flank wear with respect to varying feed rate have been evaluated. The results demonstrated that increasing feed rates resulted in rougher surfaces and higher tool wear. Compared to dry machining, MQL machining significantly reduced the surface roughness and tool wear by 14.31 % and 24.33 %, respectively. However, cryogenic machining performed exceptionally with a 20.6 % reduction in surface roughness and a 37.12 % reduction in tool wear based on number passes. Hence this work contributed to identifying suitable machining parameters along with a proper cooling technique for improving the tool life and surface finish during machining of Invar 36 alloy.

Major Findings: *According to this research, cryogenic machining reduced tool wear by up to 37.12% and surface roughness by 20.60% when compared to dry machining. Cryogenic machining has shown considerable advantages in turning operations, including longer tool life, higher surface roughness, making it a preferable cooling approach for machining of difficult to machine materials such as INVAR 36..*

Keywords: High-Speed Turning, Invar 36, Minimum Quantity Lubrication, Cryogenic, Surface Roughness, Flank Wear

1.0 Introduction

Nickel-based alloys are having exceptional characteristics; hence they are commonly used in high-temperature applications. However, they are difficult to manufacture to the necessary quality standards due to their difficult-to-cut nature[1]. Invar 36 is an alloy with nickel and iron in majority of its composition (64% Fe, 36% Ni). Its special characteristic is its ability to stay dimensionally stable across a wide range of temperatures, due to its extremely low coefficient of thermal expansion[2]. Machining is a challenging operation due to the intense heat generation when the cutting tool is forced to machine the surface of the work material. Hence, choosing the right cutting parameters is essential to optimizing effectiveness[3]. Choudhury *et al.* studied that cutting tools usually wear during machining operations and in general, this wear is a major problem because it may damage the machinery and reduce the product's quality[4]. Suresh *et al.* investigated that the performance of machined parts is impacted directly by surface quality, which is a major requirement for the customers[5]. Choudhury *et al.* studied that in an automated industry, it's important to give prominence to tool wear monitoring to prevent machine risk factors

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and surface finish deterioration. This allows for the introduction of a new tool when the existing one wears out, resulting in the desired end product. Cutting tools may fail due to several factors such as plastic deformation, mechanical breakage, edge blunting, brittle fracture, or increased contact temperature[6]. Sartori *et al*. investigates that cutting fluids play an essential role in machining processes. They reduce friction and power consumption, evacuate chips, and cool/lubricate the cutting zone, all of which improve the chip removal process. Additionally, there are advantages such as preserving the cutting tools from oxidation. Minimum Quantity Lubrication (MQL) is an economical and effective substitute for conventional (dry) machining technique because of its mist-based oil delivery system and low oil usage. Furthermore, cryogenic cooling is an environmentally acceptable clean technology for controlling cutting temperatures and increasing tool life. Cryogenic cooling lowers the cutting temperature significantly and that has several advantages[7]. Recent studies have investigated the relationship between cutting parameters and tool performance when machining Invar 36 alloy. Zhang *et al*. found that at cutting speed ranges of 200-250 m/min, fan-like generation of chips occurred, considerably increasing tool wear and reducing tool life to one-third of that observed at lower speeds (100 m/min). This highlights the importance of cutting speed for tool life and surface quality[8]. Mahir investigated that, when machining materials with a low heat conductivity coefficient, such as Invar 36 alloy, it is recommended that the feed rate was the most influential parameter on cutting force and R_a, resulting in 44.59% and 67.14%, respectively. Similarly, cutting speed was found as the most significant factor influencing *VB* and Power consumption, with additive rates of 44.59 % and 67.14 %, respectively[9]. Khanna *et al*. used Taguchi's orthogonal array method to optimize machining parameters for milling the INVAR-36, demonstrating its effectiveness in minimizing experimental effort. Surface roughness was primarily influenced by depth of cut, followed by cutting speed and feed rate. Specific parameter values resulted in an ideal roughness of 0.1835 µm. Contour plots provided operators with practical information when selecting parameters for increased surface finish. The study emphasizes the necessity for greater research into aspects like as tool shape and coolant conditions to improve machining results[10]. Poulachon *et al*. studied that the cutting edge undergoes initial breakdown and edge rounding at the start of cutting, and flank wear quickly increases. The flank wear eventually settles out and stays steady. The rake face then develops crater wear, which is associated with abrasive wear. Tool wear eventually becomes uncontrollable, which causes the tool tip to fail[11]. Pan *et al*. investigates that the performance and surface quality of mechanical components are significantly influenced by surface roughness. It has a major impact on parts' lifetime and effectiveness. Amplitude and spacing are the two primary parameter categories that can be used to describe surface roughness. R_a, or the arithmetic average roughness, is the most often used amplitude parameter[12].

Limited research has been conducted on the turning process of Invar 36 alloy to achieve improved surface roughness. While studies have explored various methods like MQL, EMQL, and cryogenic machining for other nickel alloys, their effectiveness for Invar 36 has not been extensively investigated[13]. In reviewing the literature, it is evident that there is a lack of comparative analysis on surface roughness and tool wear specifically for turning of Invar 36. While studies on other nickel-based alloys provide valuable insights[14]. This study is typical in that it compares dry machining, MQL and cryogenic machining (LN_2) for Invar 36 alloy, a material that has not been thoroughly explored in this context. The work addresses a gap in the literature by giving quantitative data on how cooling strategies affect Invar 36 machining performance. These findings provide useful information for improving cutting parameters and choosing appropriate cooling methods for difficult-to-machine materials.

2.0 Materials and Methods

Machining process was carried out on an Engine lathe with a maximum spindle speed of 1800 rpm and a motor power of 10 HP. The Invar 36 work material having

Table 1. Chemical composition of Invar 36

Elements	S	Mo	P	C	Cr	Si	Mn	Ni	Fe
Percentage (%)	<0.003	<0.003	0.003	0.008	0.027	0.255	0.415	36.5	Balance

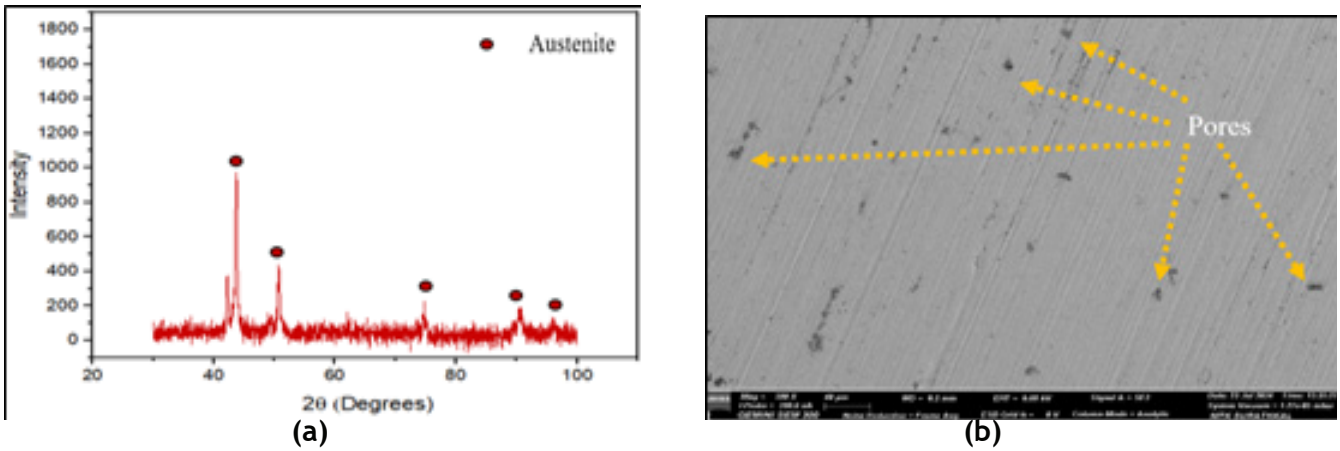
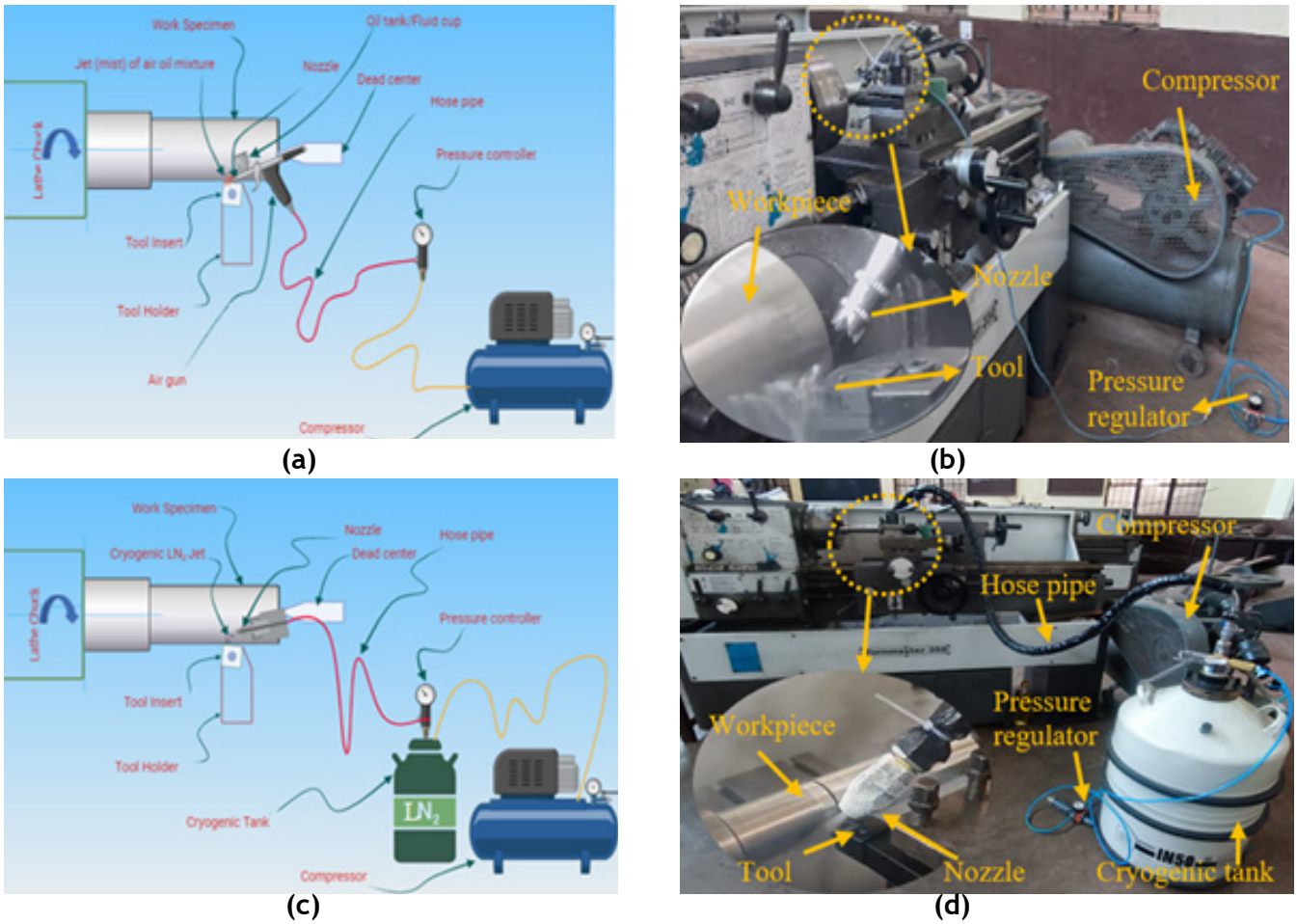


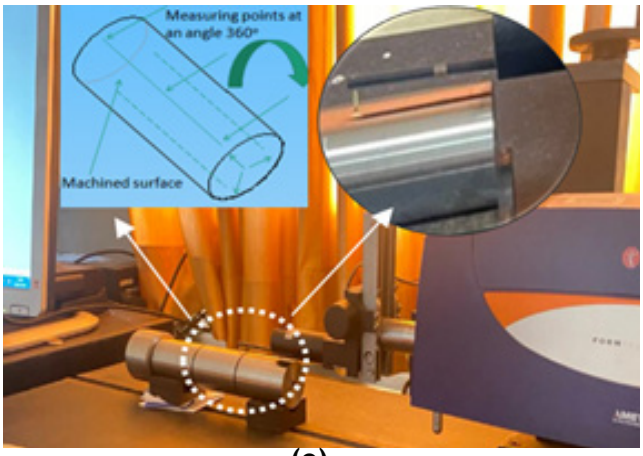
Figure 1. **(a)** XRD pattern. **(b)** Microstructure of Invar 36.

dimension of 220 mm length and 50 mm diameter is used for machining.

Table 1 shows the chemical composition of the material, which is tested using optical emission spectrophotometer (Foundry Master Smart, Hitachi).

An X-ray diffractometer (Malvern, PANalytical) has been used to obtain XRD pattern for the alloy material. Figure 1(a) shows the XRD pattern of the Invar 36 alloy material, where the reflections of the austenite FCC phase are seen[15]. SEM micrographs using FESEM (GEMINI300)





(e)



(f)

Figure 2. **(a)** Schematic representation of MQL machining **(b)** Experimental setup of MQL machining, **(c)** Schematic representation of cryogenic machining, **(d)** Experimental setup of cryogenic machining, **(e)** Surface roughness testing, **(f)** Tool wear testing.

Table 2. Machining conditions and parameters

Tool holder and insert:	
ISO catalog number/make	CNMG 120408F, TTR, KENNAMETAL
Insert IC size - D(mm)	12.7
Insert cutting edge length - L10 (mm)	12.89
Insert thickness - S (mm)	4.7
Corner radius - R	0.8
Tool holder	PCLNR 2020 K12 (SECO make)
Process parameters:	
Cutting speed (rpm)	1800
Feed rate (mm/rev)	0.18, 0.24, 0.28
Depth of cut (mm)	0.8
Environments	Dry, MQL (Canola oil), Cryogenic (LN_2)
Machining length (mm)	60 (Single pass)

showed the presence of pores evenly distributed within the austenite grains[16] (Figure 1(b)).

Before performing actual turning experiments, the work material bar is machined slightly to make three partitions, each having 60 mm length. Turning experiments are then performed considering 60 mm machining length as single pass. The hardness of the as received Invar 36 is found to be 220 HV. The tooling and machining parameters used for the present study are listed in Table 2.

In order to maximize the cooling efficiency for both MQL and cryogenic machining, the nozzle angles and distances were carefully adapted in this study. In MQL machining, the pressurized air at 7 bar is sent through a hose pipe to the air gun where it is mixes with canola oil to form a fine mist. The flow rate of the lubricant mixture is 0.0012 L/m, applied through a nozzle having diameter of 0.2 mm at an angle of 45° and a separation distance of 25 mm[17]. In cryogenic machining, the LN_2 coolant at a flow rate of 10.656 L/m is directed to the cutting zone at 0.8 bar pressure through an insulated stainless-steel hose pipe with a nozzle diameter of 4 mm over the rake face at a separation distance of 15 mm with a 30° spray angle[18]. Based on earlier research, it was discovered that these particular nozzle configurations provided the best cooling performance, greatly lowering the cutting area's temperature and enhancing the machining outcomes.

Figure 2 (a) and (b) show the schematic representation and actual experimental setup of MQL machining respectively. Figure. 2 (c) and (d) shows the schematic representation and actual experimental setup for cryogenic machining respectively. After each machining pass, the roughness (R_a) of the workpiece material

was measured using a contact type 2-D profilometer (Taylor Hobson, Taly Surf 50) at three distinct positions on the workpiece circumference, 120° apart, with a sample length of 2.5 mm (Figure 2 (c)). Also, after each machining pass, the tool insert flank wear was measured using a Tool Maker's Microscope (Mitutoyo) as shown in Figure 2 (f). Machining experiments are performed until the tool flank wear reaches a maximum of 0.4 mm (VB).

3.0 Results and Discussion

Stresses at the tool-chip and tool-work interfaces frequently approach the yield stress of the work material, separating them from conventional wear on surfaces such as bearings[19]. Figure 3 illustrates how the feed rate affects tool flank wear (VB) under three different machining conditions namely dry, MQL, and cryogenic. Higher feed rates cause an increase in tool flank wear[20] because they increase mechanical stress and friction, which in turn increases the temperature and cutting forces at the tool-workpiece interface. In the present work, all machining conditions (dry, MQL, and cryogenic) are impacted by this increased heat and pressure, which increased tool wear, particularly as more material is removed during each revolution. In dry machining (Figure 3 (a)), Controlling the machining zone temperature is critical, and cutting fluids effectively solve this problem by decreasing friction and heat buildup. Cutting fluids improve performance by providing lubrication, cooling, and chip evacuation, which help to reduce cutting forces, minimize material adhesion between the tool and the chip, and decrease heat-related issues[21]. which led to considerable increase in tool wear, particularly at higher feed rate with VB reaching the maximum value at the 10th pass (0.466 mm). MQL machining resulted in better tool performance, with all

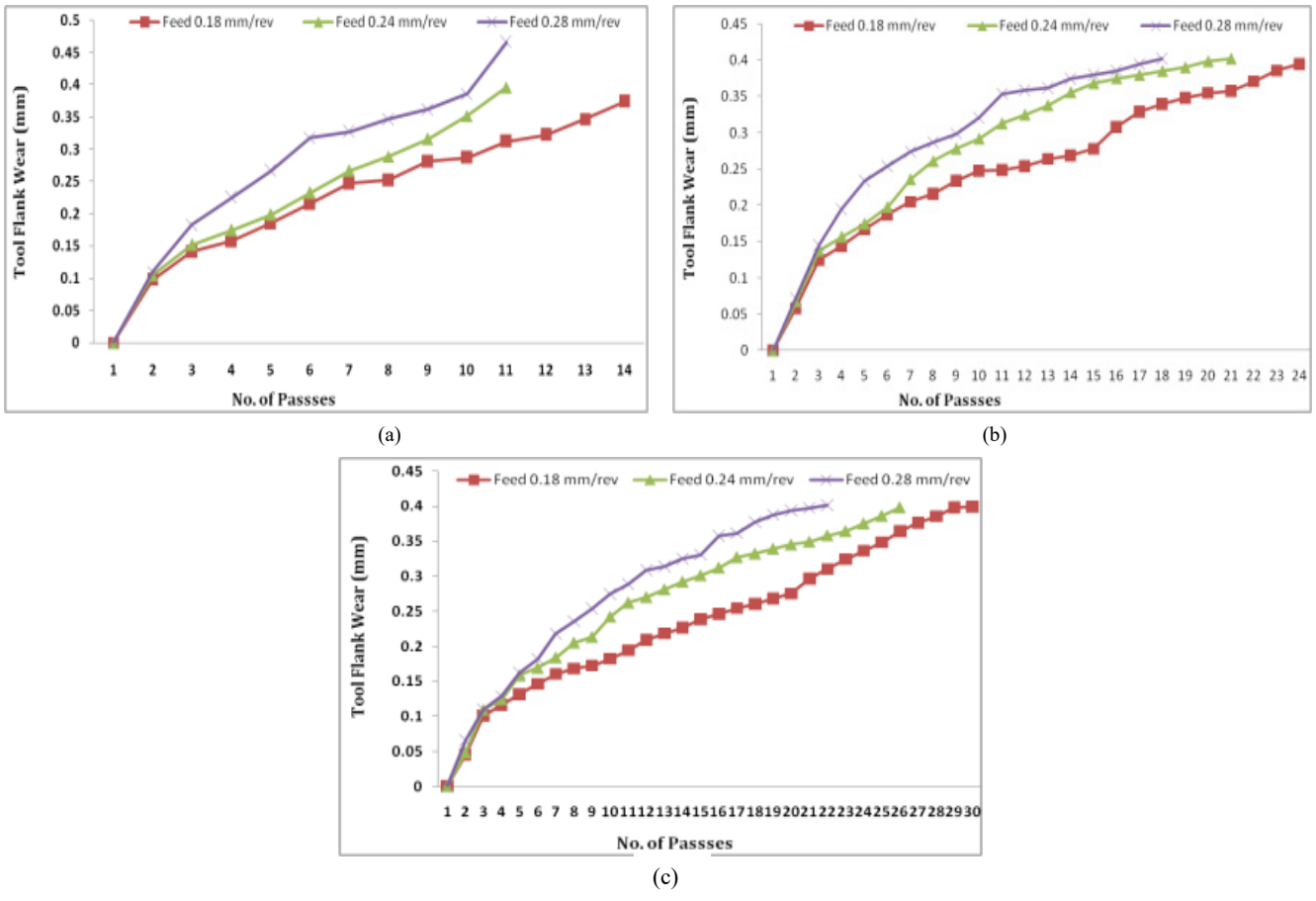


Figure 3. Effect of feed rate on tool flank wear **(a)** dry, **(b)** MQL, and **(c)** cryogenic conditions.

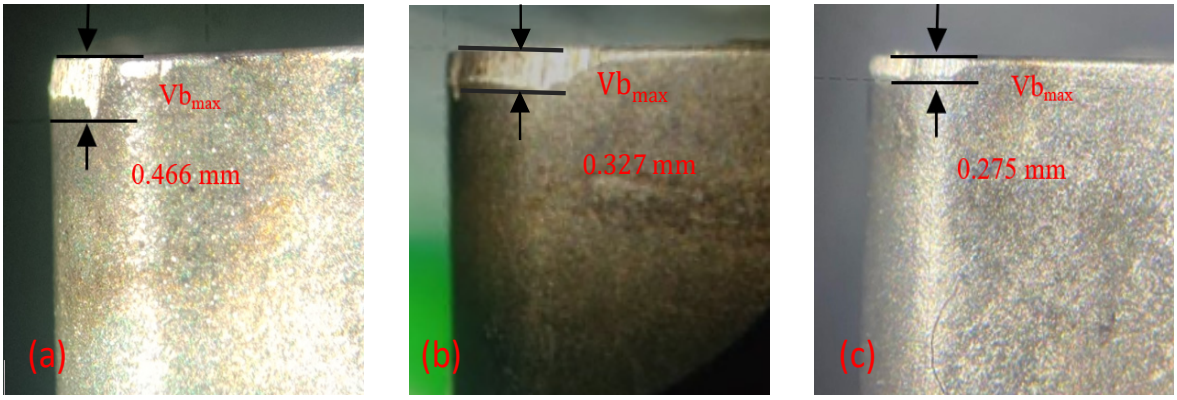


Figure 4. Tool flank wear comparison after ten passes under **(a)** dry, **(b)** MQL, and **(c)** cryogenic conditions.

three feed rate conditions performing more passes than the dry condition as can be seen in Figure 3 (b). This is because the MQL lubricates the tool, leading to reduced friction and resulting in reduced tool wear. Tool wear in cryogenic machining (Figure 3(c)) is the lowest at all feed rates, with the highest feed rate reaching up to 21 passes, when compared to the 17 and 10 passes of MQL and dry conditions respectively, to wear completely. The maximum flank wear at the 10th pass was 0.275 mm for cryogenic machining, 0.327 mm for MQL, and 0.466 mm

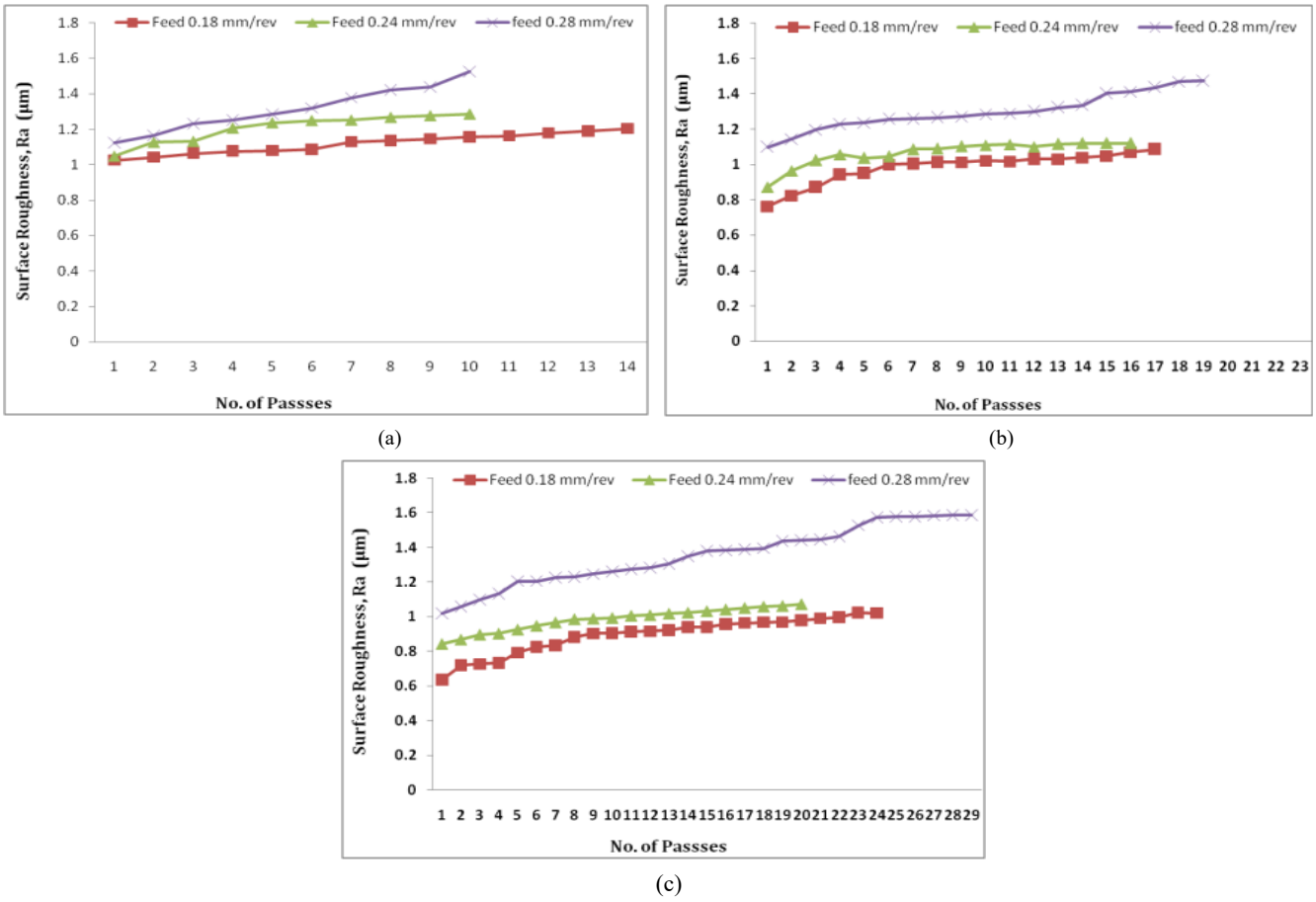


Figure 5. Effect of feed rate on surface roughness for **(a)** dry, **(b)** MQL, **(c)** cryogenic conditions.

for dry condition as clearly shown in Figure 4. Cryogenic machining significantly reduced wear by 40.99 % as compared to dry machining and 15.90 % when compared to MQL suggests a far shorter wear development demonstrating the process effectiveness in cooling and reducing friction. This results in exceptional tool life in cryogenic conditions, exceeding the benefits of both dry and MQL machining in terms of maintaining tool integrity. The graphs (Figure 3) show the experimental results, which are consistent with the normal cutting tool wear curve[22]. It is clear to distinguish the three different stages: rapid wear, constant rate wear, and rapid wear. When linked with the theoretical structure presented, a study of these graphs can yield significant insights on how particular cutting parameters and tool materials affect tool life and performance.

Figure 5 depicts the behavior of three distinct feed rates on the surface roughness (R_a, µm) under dry, MQL, and cryogenic machining conditions. Higher feed rates, in dry machining condition resulted in significantly rougher surfaces (Figure 5 (a)). Machining at higher feed rates causes vibration and increased cutting forces[23]. Surface

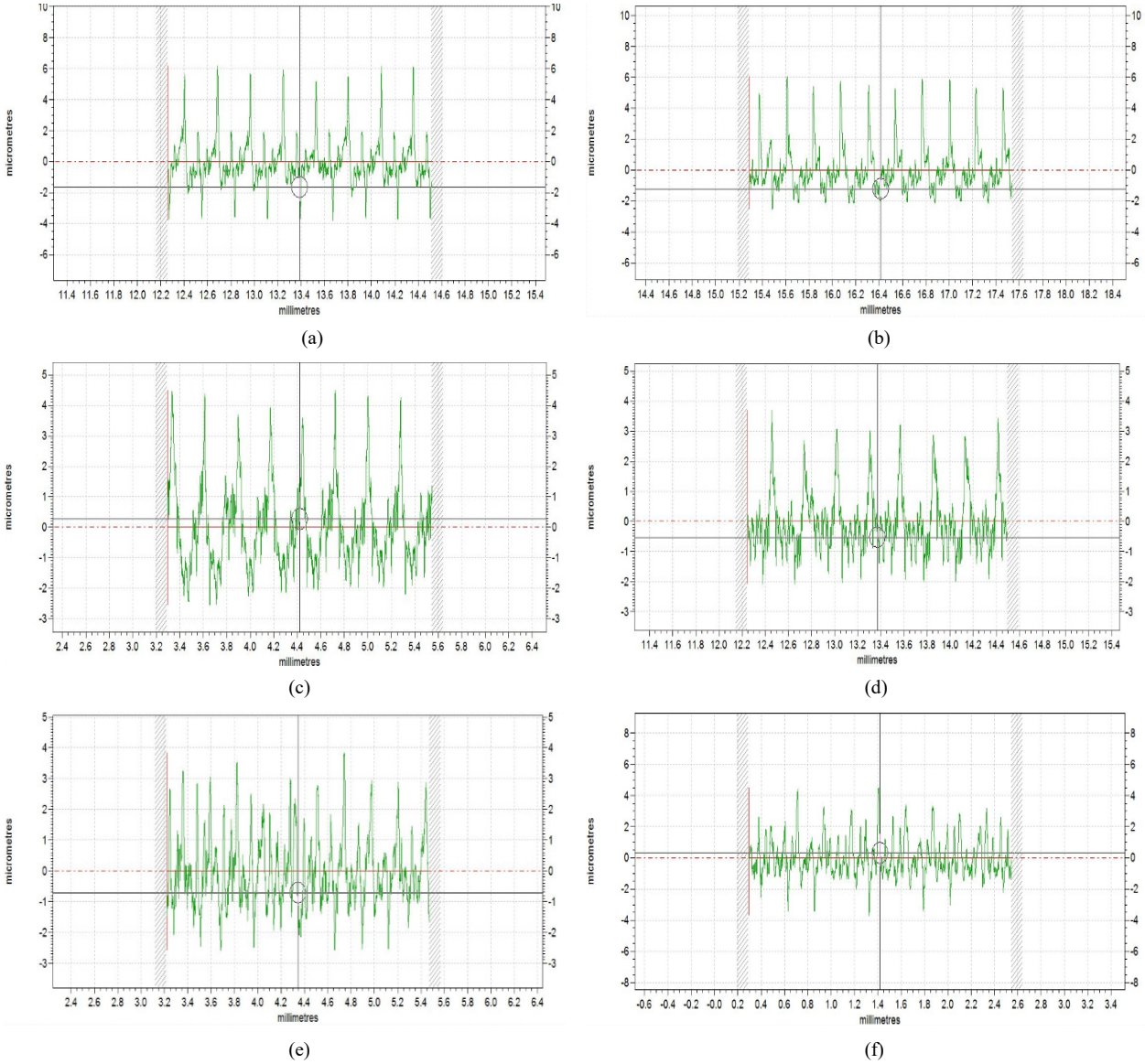


Figure 6. Machined surface roughness profile of **(a)** roughest – dry, **(b)** smoothest – dry, **(c)** roughest – MQL, **(d)** smoothest –MQL, **(e)** roughest – cryogenic, **(f)** smoothest – cryogenic.

roughness in MQL machining demonstrated a similar upward trend as feed rates increase, but it is less significant than in dry machining (Figure 5 (b)). Higher feed rates still lead to slightly rougher surfaces because of increased material removal rate, but the lubrication from MQL assists in controlling surface roughness and minimizes friction. In Cryogenic machining, surface roughness is more stable, with a less apparent increase even at greater feed rates (Figure 5 (c)). By drastically lowering heat and friction, cryogenic cooling improves surface quality and reduces the adverse impacts of increased feed rates on surface roughness. Even at higher feed rates, cryogenic machining produces the smoothest surface overall. The 2D profiles of the smoothest and roughest machined surfaces from dry, MQL and cryogenic conditions are shown in Figure 6. As compared to the high magnitude erratic peaks (y-axis) in the roughest surfaces (Figure 6 (a), (c) and (e)), the low magnitude consistent peaks of the smoothest surfaces in Figure 6 (b), (d) and (f) clearly shows the difference between these conditions.

4.0 Conclusions

This study investigated the effects of dry, MQL and cryogenic machining on the surface roughness of Invar 36 alloy and tool flank wear under varying feed rates. The following conclusions can be drawn from this investigation:

- The feed rate significantly influences surface roughness and tool flank wear, irrespective of the machining technique. Higher feed rates lead to increased surface roughness and accelerated tool wear.
- For machining Invar 36 alloy, adopting lower feed rates is essential to enhance surface quality and extend tool life.
- Compared to dry machining, MQL machining reduced tool flank wear by 24.33% based on the number of machining passes, highlighting its effectiveness in minimizing wear during machining.
- Cryogenic machining demonstrated an even greater performance, achieving a 37.12% reduction in tool flank wear and consistently delivering the lowest flank wear values (VB) across all feed rates. These results underscore the reliability of cryogenic cooling as an effective solution for enhancing tool life in turning operations.
- MQL machining performed well in producing smoother surfaces with 14.31% improvement when compared to dry machining.
- Cryogenic machining performed better by consistently generating smoother surfaces with lowest R_a values at all three feed rates with an improvement of 20.60%, when compared to dry condition.
- Cryogenic cooling is most appropriate for high-precision applications that require a superior surface finish, whereas MQL provides an affordable solution that balances performance, surface quality, and tool life.

5.0 Acknowledgments

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