Measurement and analysis of machining induced tribological characteristics in dual jet minimum quantity lubrication assisted turning of duplex stainless steel postprint

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Abstract

In this work, the sustainable machining approach is promoted by implementing the dry and minimum quantity lubrication (MQL) cooling conditions in the turning of duplex stainless steel. Initially, the turning experiments were performed under dry as well as MQL conditions and then, the influence of different positions of MQL nozzles on tribological and machining performance of 2205 duplex steel was investigated. The cutting parameters were kept fixed and the performance is evaluated in terms of surface roughness, micro-hardness, energy consumption, tool wear, machined surface microstructure and chips morphology. The results demonstrated that the highest average surface roughness values were obtained under dry conditions, with a value of 2.20 m while MQL (flank + rake directions) produces the lowest surface roughness value of 1.55 m with an improvement of 30%. Moreover, dual-jet MQL gives the lowest energy consumption (229 kJ) and tool wear (0.15 mm) with 23.67% and 52.38% enhancement, respectively.

Full Text

Preamble

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Measurement and analysis of machining induced tribological characteristics in dual jet minimum quantity lubrication assisted turning of duplex stainless steel

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This work promotes sustainable machining by implementing dry and minimum quantity lubrication (MQL) cooling conditions in the turning of duplex stainless steel. Initially, turning experiments were performed under dry and MQL conditions, and subsequently, the influence of different MQL nozzle positions on the tribological and machining performance of 2205 duplex steel was investigated. The cutting parameters were kept fixed, and performance was evaluated in terms of surface roughness, micro-hardness, energy consumption, tool wear, machined surface microstructure, and chip morphology. The results demonstrated that the highest average surface roughness values were obtained under dry conditions (2.20 µm), while MQL (flank + rake directions) produced the lowest surface roughness value of 1.55 µm, representing an improvement of 30%. Moreover, dual-jet MQL yielded the lowest energy consumption (229 kJ) and tool wear (0.15 mm), with enhancements of 23.67% and 52.38%, respectively.

1. Introduction

Stainless steel exhibits many superior characteristics such as high strength, corrosion resistance, hardness, ductility, rigidity, and heat resistance [1,2]. Compared to 304 and 316 stainless steels, duplex stainless steel offers greater corrosion resistance due to the presence of alloying elements such as nickel, chromium, and molybdenum. Duplex stainless steels with ferrite and austenite structures have become highly preferred in recent years. The ferrite structure increases resistance to mechanical and stress corrosion cracking, while the austenite structure enhances corrosion resistance and ductility. Due to these properties, duplex stainless steel is used extensively in petrochemical, mining, liquefied natural gas, nuclear power, oil and gas sectors, and its application in thin-sectioned parts provides advantages over other stainless steels [3,4]. Stainless steels are recognized as difficult-to-machine materials [5,6]. During machining, excessive tool wear occurs due to friction effects [7,8]. Chip accumulation (built-up edge, BUE) and continuous chip formation occur on the cutting edge, significantly affecting machinability [9,10]. Another issue is deformation hardening caused by thermo-mechanical effects during machining, which influences chip formation and causes vibrations, thereby severely affecting workpiece surface integrity in terms of surface roughness and residual stresses [11]. Using more rigid cutting tools and machine tools can prevent vibrations during stainless steel machining. Due to high alloying elements and austenitic structure, stainless steels form hard and continuous chips; therefore, processing with high wear-resistant carbide cutting tools with chip breakers is recommended. Low feed rates and cutting speeds are advised to prevent deformation hardening [12–14]. Carbide cutting tools possess greater strength than most other cutting tools, but suffer from brittleness and low shock resistance. Titanium and tantalum are added to overcome these limitations [15,16]. Cemented carbide is a powder metallurgy product primarily produced from different carbides (WC, TiC, TaC, or NbC) in a cobalt binder. These tools are used for difficult-to-machine materials due to their strong chemical stability, high compressive strength, hardness, hot hardness, abrasion resistance, thermal conductivity, and elastic modulus. Additionally, Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) coatings can be applied to cemented carbide tools to eliminate deficiencies of uncoated tools [17].

Metal cutting fluids significantly improve tool life and workpiece surface roughness by reducing heat and friction in the cutting zone [18,19]. Moreover, cutting fluids provide dimensional precision by reducing residual stresses through their cooling and lubricating properties [22]. Generally, cutting fluids create a boundary layer in the cutting zone through their lubrication function, resulting in improved surface roughness quality and increased tool life [23,24]. However, conventional cutting fluids are harmful to both the environment and machine operators, necessitating sustainable cooling methods to reduce costs and environmental impact [25,26]. Several cooling strategies such as cold air, cryogenic cooling, MQL, and vegetable oils are used in material removal processes [1,27–30]. These techniques enhance machining behavior and operational sustainability [31–33]. To date, MQL systems are highly recommended for difficult-to-machine materials such as titanium, nickel-based alloys, and steels [34]. Furthermore, the positioning and direction of MQL nozzles play a crucial role in enhancing machinability [35]. The effectiveness of any cooling system is determined by its direction mode, position, and type of cutting fluid used [36].

Numerous studies have investigated MQL system effectiveness. Mia and Dhar examined MQL nozzle positions in turning Ti6Al4V alloy and found duplex nozzles more efficient for lubrication and cooling than single nozzles [37,38]. Sohrabpoor et al. combined nozzle directions to the rake and flank faces in MQL turning of AISI 4340 steel, observing this method to be generally more efficient than conventional lubricant spraying [39]. Kaynak et al. compared cutting environments in machining NiTi shape memory alloys, emphasizing that MQL was superior to dry conditions in terms of surface roughness, cutting force, and tool wear [40]. Gajrani studied carbide cutting tool performance under different cooling conditions in turning Ti6Al4V alloys, highlighting that MQL was greener and cleaner than dry conditions under identical cutting parameters [41]. Zhu et al. investigated MQL superiority over dry conditions in machining Aluminum 2024-T351 alloy, finding MQL clearly better in terms of cutting temperature and tool wear [42]. Bonfa et al. compared directional MQL effects in machining D6 steel with PCBN inserts, reporting that MQL application on the rake face reduced tool wear by up to 10% compared to flank face application, with MQL demonstrating eco-friendlier effects than dry conditions regarding surface quality and tool life [43]. Touggui et al. researched AISI 304 stainless steel machinability under dry and MQL techniques, concluding MQL outperformed dry turning conditions [44].

The aforementioned studies clearly demonstrate that sustainable cooling conditions like MQL benefit machining of various materials. However, literature commonly focuses on single or dual-channel, single-jet applications to rake or flank faces. The influence of different dual-jet MQL nozzle positions on duplex steel machining performance has not been reported. In our study, the MQL mechanism employs a dual-channel system with both single and dual jets, as spray direction is a prominent parameter and machining and tribological performance are highly dependent on it. Therefore, this paper reports improvements in tribological and machining performance of 2205 Duplex Stainless Steel under a two-directional MQL system, comparing tool wear, surface roughness, energy consumption, machined surface microstructure, and chip morphology under dry conditions and MQL with different nozzle spray modes.

2. Materials and methods

2.1. Details of material, cutting tool, machine tool and cooling system

The workpiece material used in experiments was 2205 duplex stainless steel with dimensions of 50$×$250 mm and hardness of 30 HRC. The main alloying elements were nickel (~5.5%), chromium (~22%), and molybdenum (~3.0%). Coated cemented carbide cutting tools manufactured by Mitsubishi were used for machining tests, with ISO designation CNMG 120408 MM MC7025. The machining parameters were intermediate values suggested by Mitsubishi Cutting Tool Company. Fig. 1 shows the cutting tool geometry designated by the MM chip breaker, with CVD coating quality denoted by code MC7025. Machining trials were performed on a Taksan TTC-CNC setup with a 15 kW spindle and Fanuc operating system.

The Werte lubrication setup manufactured by SBH Company (Istanbul, Turkey) was used for the MQL system. The manufacturer installed an extra air pump to deliver cutting fluid (WerteMist) from two positions. Table 1 provides characteristics of Werte STN15 and WerteMist lubricant based on non-hazardous triethanolamine [45,46]. WerteMist is a special volatile lubricant. An optimum air pressure of 5 bar and flow rate of 100 ml/h were used for turning experiments, as recommended by the MQL manufacturer; these values could be adjusted via an air flow regulator and PLC control unit. MQL was delivered at three positions: MQL1 (rake face, 100 ml/h), MQL2 (flank face, 100 ml/h), and MQL3 (rake face, 50 ml/h + flank face, 50 ml/h), with total flow rate kept constant as supported by literature [47,48]. Nozzle tips for both rake and flank sides were located 45 mm apart and at a 45° angle to the tool nose [49]. Cutting parameters were intermediate values suggested by Mitsubishi Cutting Tool Company. Table 1 also shows cutting settings for turning trials, including parameters and four cutting environments.

2.2. Machining of responses

This work measured surface roughness, energy consumption, tool wear, microstructure, and micro-hardness values. Fig. 1 shows power consumption measurement in dry and MQL conditions using a KAEL Network Analyzer (Istanbul, Turkey), which precisely measures power at different CNC machining stages. Three 60/5A current transformers measured power, and energy consumption was calculated from power data using Eqs. (1) and (2).

$$\text{Energy} = \text{Power} \times (1000 \times V) / (L \times f \times N)$$

where L is cutting length in mm, f is feed rate in mm/rev, N is rpm, V is cutting speed in m/min, and D is workpiece diameter in mm.

Average surface roughness (Ra) for each condition was measured using a Mahr M300 surface roughness profilometer. Four measurements were collected by rotating the workpiece 90° and taking an arithmetic average. Tool wear images were captured using a Huamao stereo microscope at consistent magnifications. Measurements were taken at 1000 mm, 2000 mm, and 3000 mm cutting lengths, with ISO standard 3685 tool wear criterion (Vb = 0.3 mm) used for comparison. Values were measured three times and averaged for analysis.

Worn tools, separated chips, and machined surfaces after 3000 mm cutting length were examined via scanning electron microscope (SEM). The chemical composition of the cutting zone was determined using Energy Dispersive X-Ray (EDX) Spectrometry on chips and inserts. Microstructures and microhardness of machined surfaces were analyzed for each cutting environment. Specimens were initially cut and embedded in bakelite, then ground with 600, 800, 1200, and 2500 grit sandpapers, followed by etching (3 ml HNO_3 + 1 ml HCl, immersed for 30 min) for microstructure analysis. Microstructures were analyzed using a Nikon Eclipse MA200 inverted microscope. Microhardness was determined via QNESS Q10 A+ Microhardness tester using HV1 (1 kgf) Vickers hardness.

3. Results and discussion

3.1. Evaluation of surface roughness

After machining, the workpiece is expected to meet desired size and tolerance values, with average surface roughness commonly used to indicate overall surface quality. As average surface roughness decreases, surface quality improves. Fig. 2 shows average surface roughness variations across different cutting environments, while SEM and 3D surface images are presented in Fig. 3. Recent studies confirm that MQL application yields better surface quality [50–53].

Abas et al. [50] analyzed MQL effects from the rake face in turning 6026-T9 aluminum alloy. Gaurav et al. [51] studied MQL influence from the rake face in machining Ti-6Al-4V alloys. Yıldırım et al. [52] examined machining performance of 625 nickel alloy with coated carbide inserts using rake-face MQL. These authors reported surface quality improvements of 30%, 25%, and 20% under MQL conditions, respectively. The sprayed lubricants in MQL technique protect tool-workpiece contact films by reducing the friction coefficient (CoF) [54]. Marques et al. [53] studied MQL from the flank face in turning Inconel 718 alloy, reporting 35% reduction in average surface roughness values. These studies demonstrate that MQL nozzle direction is important for surface quality improvement in modern material machining.

In the current study, cutting environments were dry, MQL to rake (MQL1), MQL to flank (MQL2), and MQL to both flank and rake (MQL3) faces. At constant cutting parameters, MQL1 conditions improved surface quality by 16.3% compared to dry conditions. MQL2 performed better than both MQL1 and dry conditions by 9.43% and 24.2%, respectively. This occurs because cutting depth is much larger than tool nose radius, meaning cutting fluid completely penetrates the workpiece and is more affected by the flank face than the rake face. However, MQL3 achieved the best surface quality due to more durable protective film formation at the tool-workpiece contact area, as confirmed by EDX analysis in Fig. 8b, c, d. Experimental results showed the highest average surface roughness (2.20 µm) under dry conditions, while MQL3 produced the lowest surface roughness (1.55 µm), followed by MQL2 (1.66 µm) and MQL1 (1.84 µm). MQL3, particularly when sprayed from both faces, was most effective on Ra values, resulting in good surface finish. This mechanism is supported by burning effects observed under different cooling conditions (Fig. 3), facilitated by volatile lubricant penetration into the cutting area, reducing tool-workpiece friction [55]. MQL3 provides strong cooling and lubricating effects through compressed air and cutting fluid, creating a cushioning effect between tool and workpiece. Consequently, fewer vibrations are generated and surface quality improves. The dual-jet mechanism also reduces built-up edge (BUE) formation at the cutting tool, improving tribological characteristics through less adhesion, reduced plastic deformation, better surface finish, lower tool wear, and easier chip removal.

3.2. Energy consumption

A CNC machine tool comprises several operational elements: spindle system, linear drive system, and standby system. The spindle rotor initiates tool/workpiece rotation, feed motors provide linear or rotary movement, the hydraulic system delivers clamping force, and the tool arm motor changes cutting tools. Cooling systems and accessories also consume power during machining. This work considers power used to operate the air compressor and MQL system for analysis. Machine tool design depends on maximum energy requirements during material machining; therefore, optimizing machining parameters for minimum energy consumption is essential for sustainable manufacturing.

Fig. 4 shows energy consumption values from turning tests under various cutting environments. Energy consumption follows the same trend as surface roughness, with maximum energy consumption (299.7 kJ) under dry conditions. Compared to dry machining, MQL1 reduced energy consumption by 11.67%, MQL2 by 16.67%, and MQL3 by 23.67%. In dry machining without lubricant, greater energy is required for shear deformation and overcoming tool-chip interface friction. MQL creates better machining conditions, easier material deformation, and improved chip flow, reducing energy consumption. Enhanced lubricity at tool-work and chip-tool interfaces lowers energy consumption, particularly with MQL3 application. Lubricants reduce total energy consumption by decreasing tool-workpiece contact and friction. Race et al. [56] compared cutting environments based on energy consumption in machining SA516 steel with carbide inserts, emphasizing MQL superiority over dry and flood cooling due to reduced friction and temperature difference between tool and workpiece. Fig. 5 shows energy consumption distribution: machining power consumed 40% of energy, followed by standby power, linear motor power, spindle motor power, and MQL system power. Therefore, strict control of machining power through process parameters and cutting conditions is necessary.

3.3. Tool wear analysis

Various wear mechanisms affect cutting tools during machining, creating specific damage based on dominant mechanisms in the cutting area. The most significant wear type is flank wear, occurring at both main and auxiliary cutting edges. During chip removal, the main cutting edge performs actual cutting while the auxiliary edge determines dimensional tolerance and surface quality. Main cutting edge wear involves large forces and high temperatures, which increase with cutting speed. Increased cutting speed generates small fractures (chipping) at the cutting edge, leading to high surface roughness. Therefore, MQL was employed to improve surface and tool properties.

Szczotkarz et al. [29], Chen et al. [54], and Ozbek and Saruhan [57] investigated MQL superiority over dry conditions in machining 316L stainless steel, TiB_2/7075 aluminum alloys, and AISI D2 steel, respectively, proving MQL slows tool wear compared to dry conditions. While these studies used one-dimensional nozzle lubrication, the novelty of this work is spraying lubricant to both insert faces using MQL3. Tool wear values at 1000 mm, 2000 mm, and 3000 mm cutting lengths are shown in Fig. 6, with 0.3 mm wear criterion based on literature [58,59].

MQL1 reduced tool wear by 36.5% compared to dry conditions, while MQL2 achieved 42.9% reduction compared to dry conditions and also outperformed MQL1. MQL3 accomplished the least tool wear due to more homogeneous atomized lubricant distribution between tool and workpiece, achieving a flank wear value of 0.15 mm. Fig. 6 shows tool wear increased with cutting length from 1000 mm to 3000 mm across all conditions, following the order: MQL3 < MQL2 < MQL1 < dry. For MQL3, wear values increased by 111.3% and 183.1% when cutting length increased to 3000 mm, showing similar trends across all MQL applications (Figs. 6 and 7). These findings indicate MQL applications, particularly mixed MQL technique, significantly impact tool wear. Burning effects with cooling condition changes are visible in optical images (Fig. 7), with detailed mechanisms shown in Fig. 8. Examination of Figs. 7 and 8 reveals flank wear mechanisms in carbide inserts along with adhesive BUE formations. Cutting tool tips cannot cut with real cutting edges; formed BUEs act as cutting edges, preventing wear on tool cutting edges. High temperatures in high-speed machining of 2205 duplex steel caused prominent tool wear in dry conditions. One-directional MQL1 and MQL2 provided better performance regarding tool wear (Fig. 8b and 8c) at 0.2 mm/rev feed rate and 200 m/min cutting speed. However, two-directional MQL3 was most effective, achieving least flank wear (Fig. 8d). EDX analysis shows BUE formation consists primarily of carbon element "C," while the protective film phenomenon of triethanolamine-based WerteMist lubricant is confirmed by detection of "N," the main element of triethanolamine (Fig. 8b, 8c, 8d).

3.4. Microstructure and micro-hardness of the machined surfaces

Significant tool wear over time causes cutting tools to lose cutting capability. Continuing machining with worn tools decreases surface quality. Machinability can be explained through microstructure examination. The microstructure (Fig. 9) shows ferrite (black) and austenite (white) grains in the workpiece material. Ferrite grains are soft and ductile, while austenite is less present in machined material under dry conditions, meaning the material maintains higher hardness since less ferrite (more austenite) indicates a harder form. While austenite is the high-temperature phase of stainless steels, it is predominantly included when material is exposed to high temperatures in dry turning. Ferrite grain sizes increased with MQL1, MQL2, and MQL3, respectively (Fig. 9). The affected depth on machined surface was influenced by cutting parameters, with transition from dry to MQL conditions resulting in relatively deeper microstructure alteration. Increased affected depth could be attributed to an expanding area on the machined surface where temperature exceeded austenitization temperature, allowing subsequent quenching via lubrication effect. Higher temperature rises around insert edge tips caused localized thermal softening in workpiece material [60].

Microhardness measurements indicated that affected layers were significantly related to additional tempering during machining, resulting in lower hardness. Since temperature was insufficient at certain distances from the surface for phase transformation and cooling time was longer, a tempering effect was produced. Microhardness of machined surfaces correlated with microstructure: dry-machined workpieces exhibited higher hardness, while MQL conditions produced lower hardness (Fig. 10). Ferrite grains increased with MQL techniques since workpieces experienced high temperature followed by rapid cooling, similar to annealing heat treatment. Khanna et al. [1] compared microstructures for different cooling methods (flood, MQL, cryogenic) in turning 15-5-PH stainless steel, and Marques et al. [53] investigated microstructure after MQL turning of Inconel 718 alloy. These authors found MQL produced coarser grains than dry turning, making MQL-machined workpieces softer than dry-machined ones, consistent with our study.

3.5. Chip morphology

Chip formation is a prominent machining index that significantly affects machining performance and causes high energy consumption. By analyzing workpiece conversion into chips and flow behavior across insert surfaces, difficulties associated with process costs and tool performance can be identified. After machining experiments, chip generation mechanisms were investigated. According to Fig. 11, MQL methods, particularly MQL3, improve chip thickness ratio by reducing chip thickness compared to dry conditions, consistent with Rahman et al. [61]. This indicates MQL reduces cutting resistance, resulting in lower energy consumption (Section 3.2). Chip shape is another important aspect investigated in this work. Fig. 11 shows various chip shapes: continuous, small, curly, etc. Continuous chips are generally unacceptable as they directly affect workpiece surface finish, a phenomenon observed in dry conditions. MQL conditions help break chips into small pieces, resulting in better surface finish. Fig. 11 shows chip shapes, with acceptable forms produced in MQL3 conditions due to dual nozzle effects. Chip removal using carbide tools produced large pitch chips with good serration in dry turning, a mechanism also observed by Gupta and Sood [62] in machining titanium and Inconel alloys. Fig. 11a shows scaly chip structure under dry conditions, while chip tooth formation is visible in Fig. 11b, 11c, and 11d for MQL1, MQL2, and MQL3 machining, respectively. Although tooth degree is unclear in dry conditions, MQL technology facilitates chip removal with reduced friction coefficient at the tool-workpiece interaction area, making removed chips smoother in MQL turning. Significant changes were observed in chip shape depending on machining with coated carbide tools. The adhesive wear mechanism was determined by wear and workpiece characteristics. As expected, duplex 2205 stainless steel demonstrated excellent performance in MQL method at high cutting speeds. MQL3 technology produced chips with lamella structure exhibiting maximum machinability. Lamella-structured chips have also been observed in MQL machining of other engineering materials like Ti6Al4V and Inconel 751 alloys [63,64]. Chips formed by MQL3 turning have clear layered structure (Fig. 11d), improving machinability because MQL3 technique excessively reduced friction coefficient between tool and workpiece. Consequently, considerable disparity was noticed in chip morphology when turning with coated carbide tools. The adhesive wear mechanism was decisive due to wear and duplex stainless steel properties. Duplex 2205 stainless steel demonstrated excellent performance in MQL method at high cutting speeds.

4. Conclusions

This study investigated tool wear, surface roughness, energy consumption, microstructure, microhardness of machined surfaces, and chip morphology in two-directional MQL machining of 2205 duplex stainless steel. Key findings are summarized below:

- Surface roughness values were reduced under MQL3 conditions, followed by MQL2 (flank), MQL1 (rake), and dry conditions. Less burning with smoother surfaces was observed under MQL3 conditions, attributed to better lubrication effects at the cutting zone and reduced vibrations during machining, which controlled surface roughness values significantly.

- Energy consumption varied across cutting conditions. Compared to dry machining, MQL1, MQL2, and MQL3 consumed approximately 20.0%, 25.0%, and 32.0% less energy, respectively. Minimum energy consumption (203.67 kJ) was achieved with MQL3, due to reduced forces required to plough material from the resisting surface.

- Tool wear followed the same trend as surface roughness and energy consumption. Flank wear values were lowest for MQL3 compared to MQL2, MQL1, and dry conditions. SEM observations confirmed less built-up edge formation with reduced abrasion and adhesion marks under MQL3 conditions, attributed to lower cutting temperatures and reduced cutting edge fracture compared to dry conditions.

- Microstructure and microhardness analysis revealed that MQL technique increased ferrite grains because workpieces experienced high temperature followed by rapid cooling, similar to annealing. This made MQL-machined workpieces softer than dry-machined ones, with lower microhardness values observed under MQL3 conditions.

- Chip analysis provided meaningful information about machining performance. Short and long chip types were produced under MQL and dry conditions. Short chips are favorable for machining and were predominantly produced under MQL3 conditions, as compressed air and cutting fluid helped break chips into small pieces, resulting in sound machining characteristics.

- This work has limitations that could be addressed in future research. The influence of different nozzle positions with nanofluids remains unexplored in literature. Additionally, the effect of different cutting tool geometric parameters could be investigated in future studies.

CRediT authorship contribution statement

Munish Kumar Gupta: Investigation, Formal analysis, Conceptualization, Writing –review & editing.
Mehmet Boy: Conceptualization, Writing –review & editing.
Mehmet Erdi Korkmaz: Investigation, Formal analysis, Conceptualization,

Writing -review & editing.
Nafiz Yaşar: Investigation, Formal analysis, Conceptualization, Writing -review & editing.
Mustafa Günay: Conceptualization, Writing -review & editing, Supervision.
Grzegorz M. Krolczyk: Conceptualization, Writing -review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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