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Contrasting the CNC Turning of 2205 Duplex Stainless Steel Involves Exploring the Utilization of Nano Minimum Quantity Lubrication with Both Novel Textured Tools and Untextured Tools, Aiming to Enhance Material Removal Rate and Surface Roughness

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Abstract

This study aims to compare computed numerical control (CNC) turning operations on using nano-minimum quantity lubrication (nMQL) on 2205 duplex stainless steel. The focus is on evaluating the performance of novel linear groove textured carbide tool inserts versus untextured ones. The goal is to improve both material removal rate (MRR) and surface roughness through these comparative analyses. This study focuses on enhancing a modern eco-friendly manufacturing method by altering the surface structure of the cutting tool, specifically the rake face. The aim is to improve the cutting fluid's ability to adhere to the cutting edge, thereby supporting sustainable production practices. To achieve this, a femtosecond laser technique was utilized to create a tool surface texture pattern of linear grooves. To evaluate the impact, a Jobber XL CNC turner was employed for utilizing both textured and untextured tool inserts during turning operations on 2205 duplex stainless steel. The comparison considered machining performance, MRR, and the workpiece's surface roughness (Ra). The experimental study involved two groups: the experimental group, consisting of samples machined with textured tools, and the control group, where samples were machined with untextured tools. Each group comprised 20 samples, resulting in a total sample size of 40. The sample size calculation hinged on a statistical power of 80% using G-power, with a significance level (alpha) set at 0.005. Experimental findings in turning 2205 duplex stainless steel rods showcased an average surface roughness of 1.764 µm for single linear textured tools and 2.157 µm for untextured tools. Additionally, a single-textured tool insert exhibited a higher MRR of 17.126 cc/min, surpassing the 14.193 cc/min achieved with an untextured tool insert. Independent sample t-tests revealed significant differences in surface roughness ($p = 0.009$, $p < 0.05$) and MRR ($p = 0.0072$, $p < 0.05$) under CNC turning conditions with nMQL machining. The proposed single linear groove textured tool insert demonstrated a substantial 17.12% increase in MRR and a corresponding 18.35% reduction in surface roughness compared to untextured carbide tool inserts, acknowledging the study's limitations.

Keywords

CNC turning, Duplex stainless steel, Material removal rate, Nano minimum quantity lubrication, Novel textured tool, Surface roughness

Introduction

This experimental investigation seeks to explore how the use of innovative textured tool inserts affects both the average surface roughness and MRR when turning duplex stainless steel using CNC and nMQL cutting conditions. The primary focus is to compare the performance of these newly designed textured tool inserts with their untextured counterparts. There is a growing demand for products that exhibit superior surface finishes, precise geometrical forms, and overall accuracy [1]. Nevertheless, achieving satisfactory surface quality while turning a 2205 duplex stainless rod in dry conditions poses a considerable challenge due to severe tool wear and edge degeneration caused by its extreme hardness [2]. Surface texturing represents an innovative environmentally friendly approach to manufacturing. This method concentrates on modifying the surface topography of the cutting tool at the rake face, as detailed in the research conducted. Through practical investigations, it has been confirmed that introducing textures on the rake face of the cutting tool leads to significant reductions in both the frictional force between the tool and the chip and the wear of the tool, across various machining conditions. The dry machining technique applied to hard materials induces substantial tool wear and leads to suboptimal surface quality owing to elevated temperatures in the cutting zone. Conversely, the flood cooling method employed during the turning process of duplex stainless rods exhibits detrimental environmental repercussions and poses potential health risks to operators [3, 4]. Turning is a machining technique that the manufacturing industry relies on more frequently than any other. To address environmental concerns, the current industrial focus is on low-volume lubrication machining techniques employing textured cutting tools [5].

There have been around 317 research publications exploring tool texturing and MQL machining conditions, with 102 of them available on Science Direct. Machinability, a term denoting a material's ease of machining [6], improves when certain estimators are enhanced. This improvement signifies the material's increased machinability, leading to enhanced machining performance and productivity. When turning under MQL, surface roughness values surpass those observed in normal flood cooling. Additionally, plain lubricating oil emerges as the optimal choice for effective machining lubrication [7]. This efficient lubrication reduces the friction between the cutting tool and the workpiece [8]. The use of this tool can lead to various consequences, such as financial losses due to imperfections in the workpiece or subpar surface quality. Industries involved in manufacturing are appealing due to their ability to remove material efficiently and produce high-quality products [9].

This experimental investigation aims to improve the assessment of how process parameters impact surface roughness and MRR in the CNC turning of workpieces crafted from SS 316 steel rods. To accomplish this, we employ a design of experiments approach, enabling a methodical plan for the necessary experiments that include both textured and non-textured tool inserts. Among the mentioned studies, the most noteworthy one [9].

While numerous studies explore the machinability of different materials and alloys, few closely resemble the uniqueness of this particular work. Despite the identification and testing of several distinct textured cutting tools in the machining of diverse workpiece materials, drawing definitive conclusions regarding the most efficacious surface texture for enhancing machining performance remains challenging. We aim to investigate how the use of innovative surface-textured carbide tool inserts in a near-dry machining environment affects the average surface roughness and MRR of 2205 duplex stainless steel.

Materials and Method

The Saveetha School of Engineering, a division of the Saveetha Institute of Medical and Technical Sciences in Chennai (Tamil Nadu, India), is home to the CNC turning facility where the study was carried out. For this investigation, a 2205 duplex stainless steel rod with a 25 mm diameter and a 125 mm length was selected as the workpiece material. Table 1 displays the chemical composition of the 2205 duplex stainless steel. In this study, we're comparing the performance of an untextured carbide tool insert with that of a distinctively textured tool insert used in the CNC turning process. Two separate teams are collaborating on this project. The experimental group is using the new CNGA 120804 with a linear groove texture, while the control group employs the same insert without any texture. Each group has a total sample size of 13, with a mean ranging from 744.1013 to 750.13618 and a standard deviation from 2.1568 to 1.7641. An 80% pre-test G-power was utilized.

In both sets of samples tested, we used workpieces made of 2205 cylindrical rods made of duplex stainless steel were purchased from SAAJ in Chennai (Tamil Nadu, India). These rods, with a diameter of 25 mm and a length of 126 mm, were specifically designed for turning experiments. To ensure the authenticity of the material, the chemical composition of the 2205 duplex stainless steel was verified and certified by MET Mech LAB in Chennai (Tamil Nadu, India). The chemical composition is summarized in table 1. In the experimental group, turning trials were carried out using a Box-Behnken design within the response surface methodology. 20 turning experiments were conducted using a novel linear groove textured CNGA 120804 tool insert in a CNC lathe.

In the control group samples, 20 turning process experiments were run using an untextured new CNGA 120804 tool insert in a CNC lathe. Graphene based nanofluids in nMQL conditions for cooling and lubrication promote sustainable production [10].

MQL set-up

The flow rate on the nMQL equipment was set at 120 ml/h. Through a pressure regulator with a 4-bar setting, the system was linked to the compressed air. It features two separate mechanisms for controlling the oil/air flow. Two separate coaxial tubes are used to supply the air and lubricant flows to the 2 mm-diameter nozzles; the terminal section is where the

Table 1: The makeup of round bars crafted from 2205 duplex stainless steel.

Grade	2205 (S31083)	
	Min	Max
C	-	0.030
Mn	-	2.00
Si	-	1.00
P	-	0.030
S	-	0.020
Cr	21.0	23.0
Mo	2.5	3.5
Ni	4.5	6.5
N	0.08	0.20

oil is mixed and nebulized. In the current work, neat castor oil blended with graphene nanoparticles used as nanofluids. It is made of renewable raw materials, is non-toxic, and promotes sustainable production.

We used the Mitutoyo-SJ-410 surface roughness tester to determine the average surface roughness (Ra), with a sampling length of 4 mm. For each of the 20 samples, three readings were recorded, and the corresponding values for average surface roughness were then organized in table 2. The MRR demonstrates a direct proportional correlation with the production rate. A higher MRR value corresponds to increased productivity, while a lower MRR value is associated with reduced productivity. We used equation 1 on every sample to perform the calculation.

$$MRR\ (cc/min) = D \times F \times S \quad (1)$$

Where D is depth of cut (mm), F is feed rate (mm/rev), and S is cutting speed (m/min).

Statistical analysis

Following the experimental trials, we documented the MRR and average surface roughness. Statistical significance comes into play when the observed p-value is less than 0.05. The dependent variables in this study are surface roughness and MRR, and feed, speed, and tool nose radius are the independent variables. In the process of analyzing data to evaluate the impact of using both textured and untextured tool inserts for turning 2205 duplex stainless steel, we employed the independent t-test to scrutinize the results and detect any statistical significance [11].

Results

The new method for texturing carbide tool inserts designed for green machining on a CNC turning machine for 2205 duplex stainless steel results in an average MRR of 17.126 cc/min. In contrast, tool inserts without texturing have an average MRR of 14.193 cc/min. Additionally, the suggested texturing technique produces an average surface roughness of 1.764 µm, while traditional turning generates a higher surface roughness of 2.549 µm. Hence, better machinability was observed in the proposed method.

Table 1 displays the chemical composition of 2205 duplex stainless steel round bars. In table 2, various input parameter combinations are presented, facilitating a performance comparison between a novel single linear groove textured carbide tool insert and an untextured carbide tool insert.

The resulting output parameter, surface roughness, is determined and tabulated. In table 3, you can see the MRR values that were calculated for both new textured tool inserts and those without texture. The values take into account factors like speed, feed, and tool nose radius. the group statistics for surface roughness performance obtained from the independent t-test are outlined in table 4. Table 5 presents the results of the independent sample t-test and the significance test for surface roughness observations. Table 6 displays the group statistics for MRR performance, determined through an independent t-test. Table 7 shares the outcomes of both the t-test and independent samples test in examining MRR observations.

Figure 1 illustrates the procedure for the preparation of graphene nanofluid. Figure 2 shows the CNC lathe along with

Table 2: The outcomes of experiments on surface roughness and the corresponding input parameter settings during CNC turning with a newly designed textured tool and conventional untextured tool inserts are presented.

S. No.	Cutting Speed, Vc (m/min)	Feed rate, f (mm/rev)	Tool nose radius, Nr (mm)	Surface roughness, Ra (µm)	
				Untextured tool inserts	Single textured tool inserts
1	55	0.12	0.2	3.340	2.678
2	113	0.12	0.2	1.821	1.505
3	55	0.22	0.2	3.022	2.437
4	113	0.22	0.2	1.507	1.246
5	55	0.12	0.8	2.736	2.207
6	113	0.12	0.8	1.765	1.423
7	55	0.22	0.8	2.411	2.026
8	113	0.22	0.8	1.642	1.324
9	35	0.12	0.4	3.246	2.715
10	133	0.17	0.4	1.793	1.546
11	84	0.09	0.4	1.669	1.346
12	84	0.25	0.4	1.935	1.561
13	84	0.17	0.4	2.372	1.913
14	84	0.17	0.80	2.120	1.710
15	84	0.17	0.4	1.966	1.585
16	84	0.17	0.4	1.510	1.325
17	84	0.17	0.4	2.198	1.773
18	84	0.17	0.4	2.015	1.625
19	84	0.17	0.4	2.270	1.831
20	84	0.17	0.4	1.776	1.505

Table 3: Output parameter MRR and their input parameter levels in the CNC turning process using novel textured tool and untextured tool inserts.

S. No.	Cutting Speed, Vc (m/min)	Feed rate, f (mm/rev)	Tool nose radius, Nr (mm)	MRR (cc/min)	
				Untextured tool inserts	Single textured tool inserts
1	55	0.12	0.2	6.60	7.68
2	113	0.12	0.2	13.56	16.41
3	55	0.22	0.2	12.10	13.79
4	113	0.22	0.2	24.86	30.08
5	55	0.12	0.8	6.60	8.03
6	113	0.12	0.8	13.56	16.41
7	55	0.22	0.8	12.10	14.46
8	113	0.22	0.8	24.86	30.08
9	35	0.12	0.4	4.20	5.21
10	133	0.17	0.4	22.61	27.36
11	84	0.09	0.4	7.56	9.15
12	84	0.25	0.4	21.00	25.62
13	84	0.17	0.4	14.28	17.28
14	84	0.17	0.80	14.28	17.28
15	84	0.17	0.4	14.28	17.28
16	84	0.17	0.4	14.28	17.28
17	84	0.17	0.4	14.28	17.28
18	84	0.17	0.4	14.28	17.28
19	84	0.17	0.4	14.28	17.28
20	84	0.17	0.4	14.28	17.28

Table 4: Group statistics outcomes for both the control and experimental groups. The averages for surface roughness, along with their corresponding standard deviation and standard error, are presented below.

	Group	N	Mean	Std. deviation	Std. error mean
Average surface roughness	Control group	20	2.1568	0.55436	0.12396
	Experimental group	20	1.7641	0.44172	0.09877

Table 6: The control and experimental groups' statistics have been compiled, detailing the MRR's mean, standard deviation, and standard error mean.

	Group	N	Mean	Std. deviation	Std. error mean
MRR (cc/min)	Control group	20	14.192	5.68256	1.2706
	Experimental group	20	17.163	6.87407	1.5370

the MQL setup used for turning experiments. The carbide tool inserts CNGA 120408 used for experimental trials is shown in figure 3. In figure 4, you can observe the CNGA 120408 insert, featuring a solitary linear groove texture. This insert comes with specific dimensions, including an 80° included angle, features a fixing hole measuring 3.81 mm in diameter, a thickness of 4.8 mm, and a corner radius of 0.8 mm.

Figure 5 introducing the Mitutoyo SJ-410 surface finish analyzer, used to perform measurements of surface roughness. Additionally, figure 6 and figure 7 showcase bar graphs generated from the results of the independent sample t-test, focusing on observations related to surface roughness and MRR, respectively.

Discussion

The results from the experiment show that the suggested tool with a single-linear groove texture outperforms the traditional untextured carbide tool insert in terms of both MRR and surface finish. According to the t-test outcomes, there is statistical significance in MRR observations, with a two-tailed p-value of 0.009 ($p < 0.05$). Additionally, for observations on surface roughness, the p-value is 0.0075 ($p < 0.05$). Consequently, the observations align with statistical assumptions and do not contravene them.

Achieving the best possible surface finish faces various hurdles, including factors like tool geometry, the microstructure of the workpiece, the way the tool and workpiece interact, the formation of build-up edge, dynamics at the chip interface, and more [12]. When the cutting speed reached 55 m/min, the highest recorded surface roughness was 3.340 µm. As the cutting speed increased, there was a corresponding reduction in surface roughness. This shift is linked to the generation of built-up edge at slower cutting rates, which adversely affects surface quality [9]. The highest average MRR achieved using a single linear groove textured insert was 27.36 cc/min. This took place when the cutting speed was at its maximum of 133 m/min, with a feed rate of 0.17 mm/rev and a nose radius of 0.4 mm. These outcomes are consistent with Kaladhar [9]. Detailed investigations demonstrated that texturing the rake face with a groove aspect ratio of 0.6 and a groove spacing of 90 µm led to significant reductions in overall thrust forces. Specifically, at cutting speeds of 80 m/min and 140 m/min, the thrust forces decreased by around 10.57% and 14.68%, respectively. These findings corroborate with the results [9, 13].

The limitations of this study pertain to the textured linear groove spacing and groove aspect ratio of the textured tool inserts. This study aims to thoroughly explore how tool wear affects the texturing of rake faces. Moreover, we will assess the overall machining efficiency of uncoated tungsten carbide tools with texture.

Table 5: The results from the independent sample t-test reveal a noteworthy distinction between the control and experimental groups. The significance level, denoted by p, is 0.009, which is below the conventional threshold of 0.05. Additionally, the t-value associated with this difference is calculated to be 2.478.

Surface roughness	Levene's test for equality of variances		T-test for equality of means						
								95% CI of the difference	
	F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. error difference	Lower	Upper
Equal variance assumed	0.909	0.35	2.478	38	0.009	0.393	0.159	-0.072	0.714
Equal variance not assumed	-	-	2.478	36.2	0.009	0.393	0.159	-0.071	0.714

Table 7: The results from the independent sample t-test reveal a noteworthy distinction between the control and experimental groups. The significance level, denoted by p, is recorded as 0.0072 ($p < 0.05$), accompanied by a corresponding t-value of -1.409.

MRR	Levene's test for equality of variances		T-test for equality of means						
								95% CI of the difference	
	F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. error difference	Lower	Upper
Equal variance assumed	0.307	0.583	-1.490	38	0.0072	-2.971	1.994	-7.009	-1.066
Equal variance not assumed	-	-	-1.490	36.7	0.0072	-2.971	1.994	-7.013	-1.071

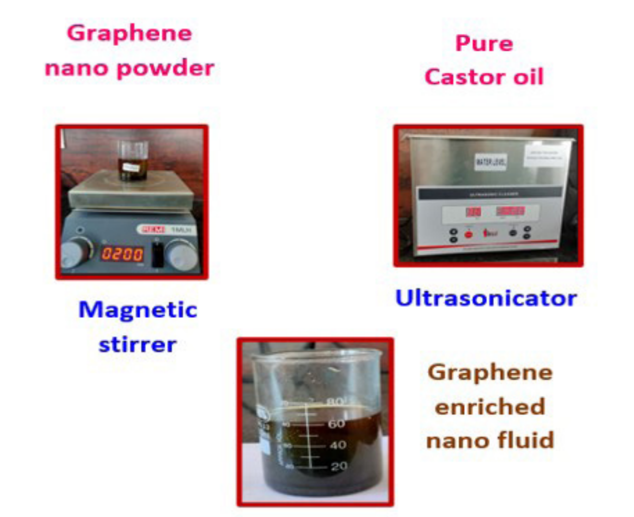

Figure 1: Graphene nanofluid preparation procedure.

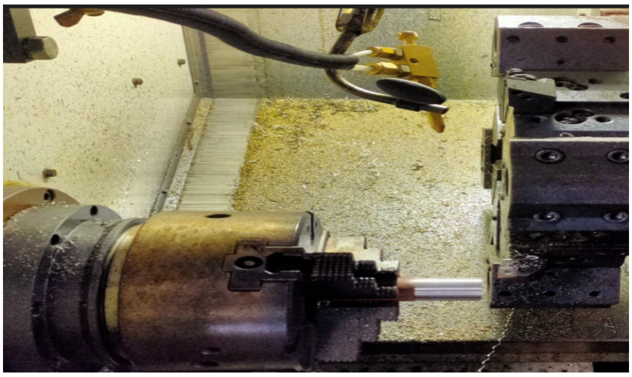

Figure 2: Jobber XL CNC lathe for the experiment, and here are the details: the carriage can swing up to 260 mm, the maximum turning diameter is 290 mm, and the turning length can reach up to 400/500 mm. The bed has a swing of 500 mm, and the spindle can spin at a maximum speed of 4000 rpm. There are 8 stations in total, and the chuck size is 200/250.

Figure 3: Carbide tool insert CNGA 120408 used for experimental study.

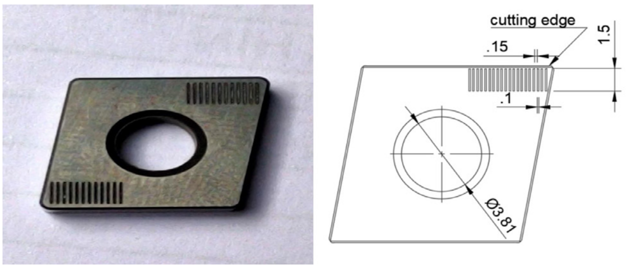

Figure 4: A CNGA 120408 insert is designed with a solitary linear groove texture, featuring an included angle of 80°. The insert has a thickness of 4.8 mm and a fixing hole with a diameter of 3.81 mm.

Figure 5: Mitutoyo model SJ-410 surface finish analyzer for surface roughness measurement.

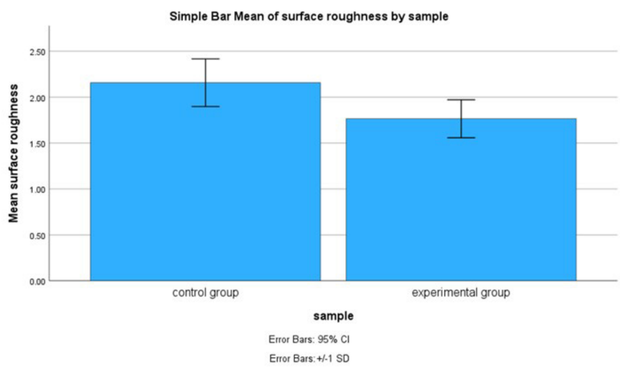

Figure 6: Contrasting the control group with the experimental group concerning surface roughness reveals interesting insights. The average surface roughness measurement for machined surfaces employing a carbide insert without texturing is a key aspect under consideration (control group) is high compared to the novel textured carbide tool insert (experimental group) and the variability in samples from the experimental group surpasses that observed in samples from the control group on the X-axis: Sample groups, Y-axis: Mean surface roughness with error ± 1 standard deviation.

Conclusion

In the investigation's limitations, the proposed cutting-edge CNGA 120408 carbide tool insert showed a boost in MRR, going from 14.193 cc/min to 17.126 cc/min when applied in nMQL machining. There has been an increase in MRR of 17.12%. The average surface roughness values obtained from the textured tool inserts were 1.764 μm, whereas the untextured tool insert yielded a roughness of 2.157 μm. Using the recently introduced CNGA 120408 carbide tool insert with a textured design in CNC turning of 2205 duplex stainless steel results in a significant decrease of 18.35% in surface roughness when compared to the performance of the non-textured tool insert.

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None.

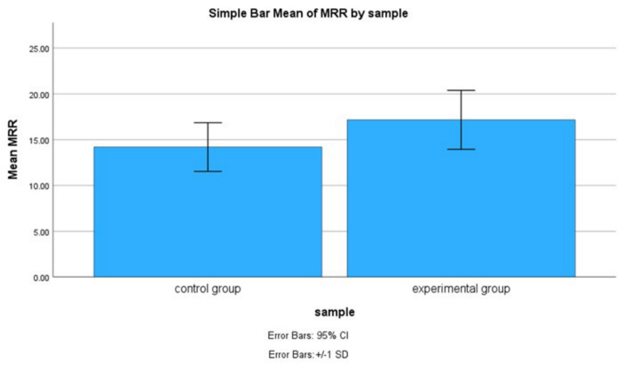

Figure 7: Contrasting the control group with the experimental group regarding the average rate of MRR reveals differences. The machined surface's mean MRRs were determined by employing carbide inserts without any texturing (control group) is low compared to the novel textured carbide tool insert (experimental group) and the variability in surface roughness among the samples in the experimental group outperforms that of the control group. On the X-axis, we have different sample groups, while the Y-axis represents the mean surface roughness, with an error margin of ± 1 standard deviation.

Conflict of Interest

None.

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