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Comparing CNC Turning of 2205 Duplex Stainless Steel Under Nano Minimum Quantity Lubrication Using a Novel Dual Textured Tool Versus an Untextured Tool to Improve Material Removal Rate and Surface Roughness

Jawahar Sivakumar and Murugaiyan Thiyagu*

Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamil Nadu, India

***Correspondence to:**
Murugaiyan Thiyagu
Department of Mechanical Engineering,
Saveetha School of Engineering,
Saveetha Institute of Medical and Technical Sciences,
Saveetha University,
Chennai, Tamil Nadu, India.
E-mail: thiyagum.sse@saveetha.com

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Abstract

Exploring the differences in cutting 2205 duplex stainless steel, this study compares new computer numerical control (CNC) techniques with tool inserts featuring both dual textures and no textures. Nano-minimum quantity Lubrication (nMQL) is employed to enhance material removal rate (MRR) and refine the surface finish. As part of contemporary eco-friendly manufacturing practices, surface texturing is applied to alter the cutting tool's surface texture on the rake face. This innovative approach enhances the wettability of the cutting fluid at the cutting edge, thereby optimizing machining performance. Using a femtosecond laser technique, a novel dual-textured tool with square and linear groove texture patterns is engraved on the tool surface. The 2205 duplex stainless steel is turned using the Jobber XL CNC turner, comparing the MRR and workpiece quality between the use of dual-textured and untextured tool inserts. Each group in the study consists of 20 samples, bringing the total sample size to 40 participants across the two groups. The calculation of the sample size was based on a statistical power (G-power) of 80% and a significance level (alpha) set to 0.0027. The experimental results show an average surface roughness of 1.764 μm for dual. When turning 2205 duplex stainless steel rod, use 2.157 μm for untextured tools and 2.05 μm for textured tools. A better MRR of 17.126 cc/min is obtained when turning with dual-textured tools when compared to 14.193 cc/min with an untextured tool insert. In the CNC turning process with nMQL machining settings, the independent t-test findings show statistical significance. (2-tailed), with $p = 0.0024$ ($p = 0.05$) for surface roughness and $p = 0.0074$ ($p < 0.05$) for MRR values. Considering the limitations of the study, the proposed dual-textured tool insert exhibited a notable increase in MRR (17.12%) and a corresponding reduction in surface roughness (19.35%) when compared to the untextured carbide tool inserts.

Keywords

Average surface roughness, CNC turning, Duplex stainless steel, Material removal rate, Novel dual textured tool, Sustainable production

Introduction

This study aims to explore the possibility of enhancing the machinability of 2205 duplex stainless steel when conducting CNC turning procedures. This will be achieved by employing a novel dual-textured tool insert and optimizing the process parameters, comparing the outcomes with those obtained using a standard stainless-steel tool insert. The goal of the research is to enhance the smoothness of the surface and increase the rate at which material is removed by implementing these interventions [1]. Because of the feature's exceptional hardness, edge degeneration makes it challenging to machine 2205 duplex stainless rod with nMQL and achieve a satisfactory surface quality in the process of the cutting effect on the spindle speed and feed rate of the surface roughness of the machining in stainless steel in the CNC turning process [2]. This study's findings can be applied to the turning process used in the automotive sector to achieve the greatest results with the fewest rejections when using 2205 duplex stainless steel and innovative dual-textured tool inserts [3]. Manufacturers, especially those in the oil and gas, petrochemical, and pulp and paper sectors, have extensively utilized duplex 2205 stainless steel in their applications [4]. People frequently opt for duplex 2205 stainless steels over austenitic counterparts because of their enhanced ability to resist chloride stress corrosion cracking and pitting, especially in environments with aqueous chloride [3].

For the turning operation, the cutting parameters selected were cutting depth, feed, and cutting speed [4]. This study focuses on enhancing the smooth surface finish and increasing the MRR in the CNC turning of aluminum alloys. The machining involves nMQL and utilizes an innovative dual-textured tool [5] to achieve these improvements. With the addition of graphene nanoparticles and castor oil for lubrication, the cutting zone temperature is reduced while machining when using nMQL [6]. In this situation, boosting performance involves using a rotary tool that applies ultrasonic vibration to both the tool and the workpiece. The synergy between ultrasonic vibration and tool rotation enhances the efficiency of the gap flushing method, leading to better MRR and surface smoothness. Moreover, ultrasonic vibration effectively removes debris from the machined area [7].

Although researchers have been actively investigating the machinability of different materials and alloys, no research with a similar focus to the current one has been found. This study aims to compare the novel dual textured CNAG 120408 tool inserts with the untextured CNAG 120408 tool inserts in terms of workpiece surface roughness and MRR in CNC turning 2205 duplex stainless steel under nMQL condition.

Materials and Method

The study took place at the CNC turning center situated within SIMATS Engineering at Saveetha Institute of Medical and Technical Sciences in Chennai (Tamil Nadu, India). The subject of the research was a rod made of 2205 duplex stainless steel, measuring 125 mm in length and 25 mm in diameter. Table 1 displays the chemical composition of the 2205 duplex stainless steel. In this investigation, we assessed the performance of a unique dual-textured tool insert employed in CNC turning, contrasting it with an untextured carbide tool insert. Figure 1 graphene nanofluid preparation. Figure 2 CNC turning - experimental set-up. Figure 3 turning inserts grade CNGA 120408 used for turning experiments. Figure 4 Dual linear groove with square textured CNGA. The insert 120408 has an 80° angle, 4.8 mm thickness, and a 3.81 mm fixing hole diameter.

This project is being worked on by two different groups. The experimental group in this study employs the new CNGA 120804 carbide insert with a surface texture comprising a linear groove and square pattern, as illustrated in figure 5. In contrast, the control group utilizes the same insert without

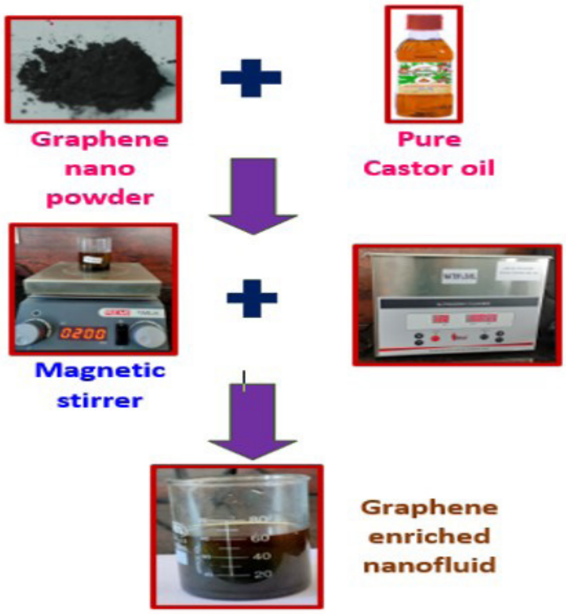

Figure 1: Graphene nanofluid preparation.

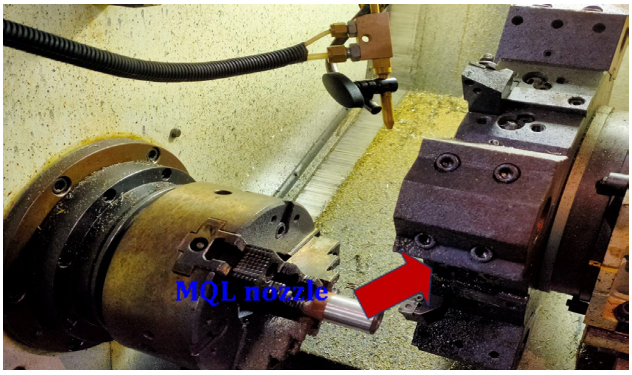

Figure 2: CNC turning - experimental set-up.

Figure 3: Turning inserts grade CNGA 120408 used for turning experiments.

any surface texture. Each group's total sample size was calculated to be 20, with a standard deviation and mean ranging from 744.1013 to 750.13618 of 2.1568 to 1.7641. A pre-test G-power of 80% was used [8-10]. Each group consists of 20 samples, with a total of 40 participants in the study—comprising a control group and an experimental group. The determination of the sample size involved utilizing a statistical power

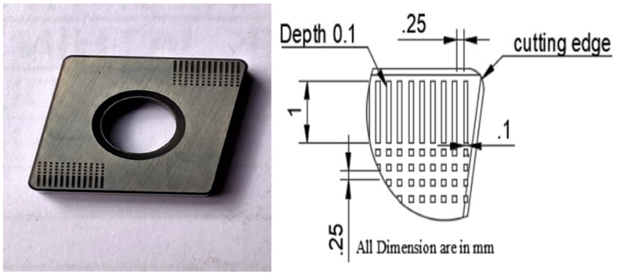

Figure 4: Dual linear groove with square textured CNGA. The insert 120408 has an 80° angle, 4.8 mm thickness, and a 3.81 mm fixing hole diameter.

Figure 5: Jobber XL CNC lathe used for the experimental setup; specs include a swing carriage measuring 260 mm, a maximum turning diameter of 290 mm, a maximum turning length of 400/500 mm, a swing bed of 500 mm, a maximum spindle speed of 4000 rpm, eight stations, and a chuck size of 200/250 mm.

(G-power) of 80% and a significance level (alpha) of 0.0024. The test workpiece samples for both groups were composed of 2205 duplex stainless steel, specifically cylindrical rods with a diameter of 25 mm and a length of 126 mm, supplied by SAAJ in Chennai (Tamil Nadu, India) for the turning experiments. MET Mech LAB, Chennai (Tamil Nadu, India), examined the stainless steel's chemical composition and verified the material's authenticity. Notably, the chemical composition of 2205 duplex stainless steel, as outlined in table 1, reveals a minimal carbon content of 0.35. Table 2 physical properties of 2205 duplex stainless steel round bar. Table 3 presents the mechanical properties of this stainless steel variant, highlighting significant yield strengths of 701.64 MPa and tensile strengths of 797.18 MPa.

Table 1: Chemical composition of 2205 duplex stainless steel round bars.

Grade	2205 duplex stainless steel	
	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

Table 2: Physical properties of 2205 duplex stainless steel round bar.

Physical properties	Value
Density	0.278 lb/in^3
Melting range	2525 - 2630 °F
Specific heat capacity at 212 °F	0.119 Btu/lb/°F
Thermal conductivity at 212 °F	8.4 Btu/hr-ft-°F
Poisson's ratio	0.3
Elastic modulus at 72 °F	29 x 10 psi

Table 3: Experimental results for surface roughness and their input parameter levels in the CNC turning process using novel dual textured tool and untextured tool inserts.

S. No.	Cutting Speed, Vc (m/min)	Feed rate, f (mm/rev)	Tool nose radius, Nr (mm)	Surface roughness, Ra (µm)	
				Untextured insert	Dual textured insert
1	55	0.12	0.2	2.526	2.088
2	113	0.12	0.2	1.816	1.476
3	55	0.22	0.2	2.892	2.390
4	113	0.22	0.2	1.478	1.222
5	55	0.12	0.8	2.792	2.164
6	113	0.12	0.8	1.689	1.396
7	55	0.22	0.8	2.404	1.987
8	113	0.22	0.8	1.506	1.245
9	35	0.12	0.4	2.821	2.371
10	133	0.17	0.4	1.359	1.123
11	84	0.09	0.4	1.597	1.320
12	84	0.25	0.4	1.852	1.531
13	84	0.17	0.4	2.270	1.876
14	84	0.17	0.80	2.096	1.677
15	84	0.17	0.4	1.881	1.555
16	84	0.17	0.4	1.572	1.299
17	84	0.17	0.4	2.191	1.739
18	84	0.17	0.4	1.929	1.594
19	84	0.17	0.4	2.044	1.689
20	84	0.17	0.4	1.786	1.476

MQL set-up

MQL system had its flow rate set at 120 ml/h, with compressed air entering through a pressure regulator set at 4 bars. This setup incorporates two distinct systems to control the flow of both oil and air. Two separate coaxial tubes deliver the air and lubricant flows to the 2 mm-diameter nozzles; the oil is combined and nebulized in the terminal section. In the current work, plain castor oil is combined with nanofluids made of graphene nanoparticles. It promotes sustainable production, is non-toxic, and is created from renewable raw materials.

In experimental group samples, the turning trials are conducted using a Box-Behnken design in response surface methodology. Twenty turning experiments were conducted using a novel linear groove-textured and square-textured CNGA 120804 tool insert in a CNC lathe [11].

In the control group samples, 20 turning process experiments were run using an untextured new CNGA 120804 tool inserted in a CNC lathe. Graphene-based nanofluids in nMQL conditions for cooling and lubrication promote sustainable production [12].

The Mitutoyo-SJ-410 surface roughness tester (Figure 6) is employed for gauging the average roughness of a surface, utilizing a sampling length of 4 mm. Three readings were taken, and the average surface roughness value (Ra) was tabulated for all 20 samples. MRR exhibits a direct proportional relationship with production rate. Consequently, higher MRR values correspond to increased productivity, while lower MRR values result in decreased productivity. Equation 1 was used to calculate the MRR for each specimen.

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

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

SPSS statistical analysis

SPSS version 26 to compute the mean, standard deviation, and standard error. The MRR serve as the dependent variables for roughness, while feed speed and depth of cut are the independent variables in this study. To evaluate the significance of employing novel dual-textured CNMG120408 inserts in comparison to their untextured counterparts for machining 2205 stainless steel, the data was analyzed using a t-test.

Figure 6: Mitutoyo model SJ-410 surface finish analyzer for surface roughness measurement.

Results

The average values for the dual-textured insert range from 744.1013 to 750.13618, with a standard deviation ranging between 0.44172 and 0.55436. In contrast, the standard error mean for an untextured insert is 40.91618, while that for a dual-textured insert is 41.91816. To assess surface roughness, a t-test was employed on distinct samples, revealing a noteworthy (2-tailed) p-value of 0.0024. The standard deviation for the dual-textured insert spans from 0.126365 to 0.126132, with the mean value falling between 0.414 and 0.314. Examining table 1, silicon (Si) exhibits the highest percentage at 0.35 and the lowest at 0.25% in the chemical composition of 2205 stainless steel. Table 2 outlines the physical characteristics of 2205 stainless steel, highlighting its elevated melting point of 1425 °C. Additionally, table 3 presents the physical attributes of stainless steel 2205. In table 4, you can find 20 distinct combinations of input parameters used to evaluate the effectiveness of a ceramic tool without texture and a special stainless-steel tool insert with dual textures. The calculated MRR values were based on speed, feed, and depth of cut for both the innovative dual-textured inserts and the untextured inserts. For the recommended and conventional machining methods, table 5 and table 7 provide a comprehensive overview of the collected data, encompassing time, measured surface roughness, and the computed MRR. Table 6 displays the results of the significance test and the independent sample test for surface roughness observations. The collective data regarding MRR performance from the t-test can be seen in table 8.

Figure 1 shows the graphene nanofluid preparation procedure. Figure 2 shows the CNC lathe along with the MQL setup used for turning experiments. In figure 3, you can observe the carbide tool inserts marked as CNGA 120408, which were employed in our experimental trials. Moving on to figure 4, it illustrates CNGA 120408 inserts featuring a single linear groove. These inserts have an included angle of 80°, 4.8 mm in thickness, 0.8 mm in corner radius, and 3.81 mm in fixing hole diameter. As depicted in figure 5, our experimental setup involved the Jobber XL CNC lathe. The surface finish analysis, shown in figure 6, utilized the Mitutoyo SJ-410 surface finish analyzer for measuring surface roughness. Turning our attention to the statistical analysis, figure 7 and figure 8 exhibit bar graphs generated through SPSS. These graphs represent the outcomes of independent sample t-tests conducted for surface roughness and MRR observations, respectively.

Discussion

The results suggest that both the linear groove textured, and square textured tools perform better than a traditional untextured carbide tool insert in terms of MRR and surface finish. The independent sample t-test shows statistical significance for both MRR ($p = 0.0074$, $p < 0.05$) and surface roughness ($p = 0.008$, $p < 0.05$). Achieving an optimal surface finish is challenging due to factors like tool geometry, workpiece microstructure, tool-workpiece interaction, build-up edge synthesis, and chip interface. At a lower cutting speed

Table 4: Output parameter MRR and their input parameter levels in the CNC turning process using novel dual 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 insert	Dual textured insert
1	55	0.12	0.2	8.118	6.600
2	113	0.12	0.2	16.136	13.560
3	55	0.22	0.2	16.335	12.100
4	113	0.22	0.2	33.810	24.860
5	55	0.12	0.8	7.986	6.600
6	113	0.12	0.8	16.408	13.560
7	55	0.22	0.8	16.456	12.100
8	113	0.22	0.8	30.081	24.860
9	35	0.12	0.4	5.628	4.200
10	133	0.17	0.4	27.358	22.610
11	84	0.09	0.4	9.148	7.560
12	84	0.25	0.4	27.090	21.000
13	84	0.17	0.4	17.279	14.280
14	84	0.17	0.80	17.279	14.280
15	84	0.17	0.4	17.279	14.280
16	84	0.17	0.4	17.279	14.280
17	84	0.17	0.4	17.279	14.280
18	84	0.17	0.4	17.279	14.280
19	84	0.17	0.4	17.279	14.280
20	84	0.17	0.4	17.279	14.280

Table 5: Group statistics result for control and the experimental group. The surface roughness mean, standard deviation and standard error mean are shown below.

	Group	N	Mean	Std. deviation	Std. error mean
Surface roughness	Control group	20	2.1568	0.46646	0.10430
	Experimental group	20	1.7641	0.37727	0.08436

Table 7: Group statistics result for control and the experimental groups. The MRR mean, standard deviation, and standard error mean are tabulated.

	Group	N	Mean	Std. deviation	Std. error mean
MRR	Control group	20	14.1925	5.68256	1.27066
	Experimental group	20	17.6392	7.28435	1.62883

Table 6: The independent sample t-test yielded noteworthy outcomes: A notable distinction emerged between the experimental and control groups, with a t value of 2.71 and a significance level of p = 0.008 (p < 0.05).

Surface roughness	Levene's test for equality of variances		T-test for equality of means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. error difference	95% CI of the difference	
								Lower	Upper
Equal variance assumed	1.09	0.30	2.71	38	0.008	0.364	0.134	0.093	0.636
Equal variance not assumed	-	-	2.71	36.4	0.008	0.364	0.134	0.092	0.636

Table 8: The independent sample t-test findings indicate a noteworthy distinction between the experimental and control groups. The calculated t value stands at -1.668, and the associated significance level is noted as p = 0.0074 (where p < 0.05).

MRR	Levene's test for equality of variances		T-test for equality of means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. error difference	95% CI of the difference	
								Lower	Upper
Equal variance assumed	0.474	0.495	-1.668	38	0.0074	-3.447	2.066	-7.628	0.735
Equal variance not assumed	-	-	-1.668	35.8	0.0074	-3.447	2.065	-7.636	0.743

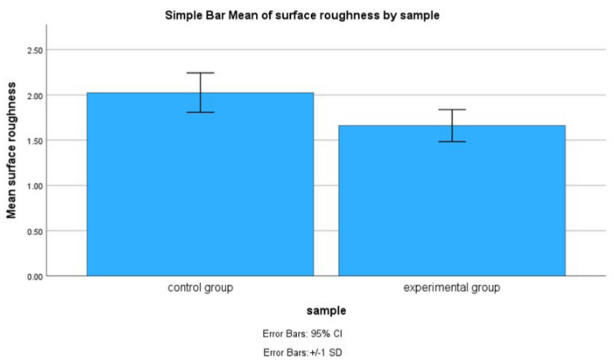

Figure 7: Comparing control and experimental groups for surface roughness, the untextured carbide insert (control) yielded higher mean roughness than the novel dual-textured carbide tool insert (experimental). Experimental group's standard deviation was better. Graphically, X-axis shows sample groups, Y-axis displays mean surface roughness with ± 1 standard deviation.

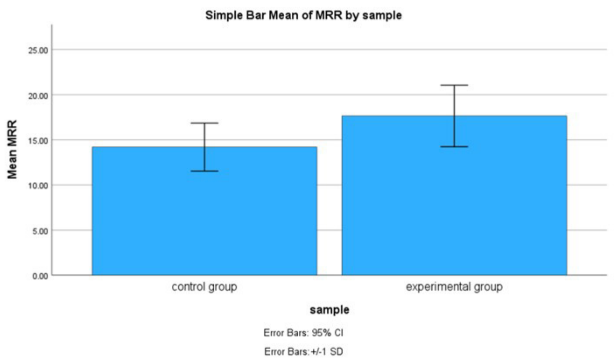

Figure 8: Comparing the control and experimental groups for mean MRR, surfaces machined with the untextured carbide insert (control) show lower rates than those with the novel dual-textured carbide tool insert (experimental). Experimental group's standard deviation is also better. Graphically, sample groups are on the X-axis, and mean surface roughness (± 1 standard deviation) is on the Y-axis.

of 55 m/min, the surface roughness reached its highest value of 2.525 µm. However, with an increase in cutting speed, the surface roughness decreased. The reason for this shift could be linked to the poorer surface quality arising from the formation of build-up edge at slower cutting rates [13, 14]. Using a single linear groove textured insert, the highest average MRR reached 27.36 cc/min, achieved under specific cutting conditions. These conditions involved a maximum cutting speed of 133 m/min, a nominal feed rate of 0.17 mm/rev, and a nose radius of 0.4 mm. The findings align with those reported by Kaladhar [14]. A quantitative analysis indicated that incorporating rake face texturing has the potential to reduce overall thrust forces by around 10.57% and 14.68% at cutting speeds of 80 m/min and 140 m/min, respectively. These reductions were observed with a groove aspect ratio of 0.6 and a groove spacing of 90 µm.

This linear groove texturing and square texturing form improves emulsion penetration and can function as a micro-reservoir for constant emulsion replenishment. As a result, better cooling and lubrication promote sustainable production [15]. The limitations of this study lie in the dual textured linear groove and square texture spacing and groove aspect ratio of dual textured tool inserts.

Conclusion

The proposed innovative textured CNGA 120408 carbide tool insert increased the MRR performance under nMQL machining settings from 14.193 cc/min to 17.126 cc/min, within the limits of the investigation. There has been a 17.12% increase in MRR. In contrast to the 2.025 µm of the untextured tool insert, the textured tool inserts produced average surface roughness values of 1.661 µm. In CNC turning of 2205 duplex stainless steel, the textured CNGA 120408 carbide tool insert exhibits a noteworthy 18.46% enhancement in surface roughness compared to the untextured tool insert's performance.

Acknowledgements

None.

Conflict of Interest

None.

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