Nano World Journal

https://doi.org/10.17756/nwj.2023-s3-188

Research Article

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# Comparative Evaluation of Cylindrical Error of CNC Turned HCHCR D2 Steel using Novel CrTiN PVD Coated with Uncoated High-Speed Steel Tools

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**Received:** July 31, 2023
**Accepted:** November 01, 2023
**Published:** November 03, 2023

**Citation:** Kumar TM, Bejaxhin ABH. 2023. Comparative Evaluation of Cylindrical Error of CNC Turned HCHCR D2 Steel using Novel CrTiN PVD Coated with Uncoated High-Speed Steel Tools. *NanoWorld J* 9(S3): S1064-S1068.

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## Abstract

This study aims to conduct a comprehensive comparative analysis of cylindrical error (CR) in the CNC turning of HCHCR D2 steel using novel CrTiN physical vapor deposition (PVD) coated tools versus uncoated high-speed steel (HSS) tools. The research involved HCHCR D2 steel as the work material and employed both CrTiN PVD coated and uncoated tools. Key input parameters, including cutting speed, feed rate, and depth of cut, were systematically varied across four distinct levels, resulting in 32 samples (16 for each tool type) analyzed under CNC machining conditions with a sample size at G power 80%. The findings unequivocally demonstrate that the use of novel CrTiN-coated HSS tools led to a substantial reduction in CR compared to uncoated HSS tools. The statistical significance, as indicated by a p-value of 0.000 (both 2-tailed), highlights the robustness of this improvement and establishes its statistical significance ($p < 0.05$). On average, the use of CrTiN PVD-coated tools resulted in a remarkable 24.2% reduction in CR when compared to uncoated tools during the machining of high-strength HCHCR D2 steel. This research underscores the superior performance of CrTiN PVD-coated tools, emphasizing their effectiveness in achieving higher machining precision and reduced errors. These findings have important implications for enhancing machining quality and cost-effectiveness in industrial applications involving HCHCR D2 steel.

## Keywords

HCHCR D2 steel, Cylindrical error, Novel CrTiN PVD coated tool, Uncoated high-speed steel, Statistical analysis, Sustainable production

## Introduction

This research focuses on enhancing the machinability of HCHCR D2 steel in CNC turning operations using novel CrTiN-coated tools and comparing them with uncoated tool inserts to minimize CR. Various process parameters, including cutting speed, feed rate, and depth of cut, are explored to optimize machining precision and ovality reduction. The high mechanical strength and hardness of HCHCR D2 make machining challenging, particularly in industries like automotive and tool manufacturing. The study draws from a significant body of related research, utilizing techniques like gray relational analysis and objective CNC cutting parameter optimization. The investigation aligns closely with prior work [1], which employed a coordinate measuring machine (CMM) to assess CR. This research stands out for its unique focus on reducing cylindrical ovality for machining performance improvement, utilizing novel CrTiN PVD coatings. While similar studies exist, none directly address this specific objective. It is anticipated that the novel CrTiN PVD coating will prove effective in reducing workpiece cylindrical ovality compared to uncoated tools, with implications for future advancements in machining technology and precision.

This research represents a unique and pioneering effort in the field of machining materials and alloys. While various studies have explored uncoated cutting tools and their impact on cylindrical tolerance, this investigation stands apart by focusing on the reduction of CR and ovality for machining performance enhancement. No similar publications with this specific emphasis have been identified. The future implications are promising, as the novel CrTiN PVD coating is expected to play a pivotal role in reducing workpiece cylindrical ovality when compared to uncoated tools. This breakthrough has the potential to significantly advance machining technology, improving precision and quality in manufacturing processes. The findings of this research mark a noteworthy contribution to the ongoing quest for innovation in the realm of materials machining.

## Materials and Methods

This experimental review study was conducted with the valuable support of Saveetha Industries, Saveetha School of Engineering, and Saveetha University, dividing the experimentation into two groups: the experimental group utilizing CrTiN PVD-coated tools and the control group employing uncoated HSS tools. Each group utilized workpiece samples measuring 25 mm in diameter and 60 mm in length, with a total of 16 samples for each group, resulting in 32 samples in total. Notably, this study did not involve human subjects, thus obviating the need for ethical approval. The workpiece material chosen for this investigation was HCHCR D2, characterized by a robust yield strength of 826 MPa, with mechanical properties. These workpiece samples were employed in the CNC turning process for both experimental groups, each with dimensions of 25 mm in diameter and 60 mm in length. During the machining process, four input variables were carefully controlled, with feed rate, cutting speed, and depth of cut varying at three distinct levels, ensuring a systematic exploration of the machining parameters.

In the first group, uncoated HSS TNMG 160408 (Widia) tool inserts were utilized for the CNC turning process. The HCHCR D2 steel work material was initially obtained with the specified dimensions and then subjected to a skin-cut process to eliminate any surface defects. This group produced a total of 16 samples, which were subsequently analyzed to extract relevant statistical data. In contrast, the second group employed CrTiN with PVD coating on the tool inserts. This group was considered the experimental group, while the control group continued to use uncoated HSS tool inserts [2, 3]. Both conventional and novel PVD-coated CrTiN tools were incorporated into the CNC turning process, utilizing the same HCHCR D2 steel workpiece with dimensions of 25 mm in diameter and 60 mm in length.

To evaluate the outcomes of the turning process and assess the impact of the tool inserts, a CMM was employed [4, 5]. CR measurements were taken using the CMM probe, with a sampling length of 30 mm on each finished workpiece. This measurement process was repeated on two separate samples for each study group, ensuring reliability and consistency. The average of the five CR values obtained from these measurements was utilized to calculate the cylindrical inaccuracy of the machined workpieces, following the method described by [6]. In summary, this study meticulously investigated the impact of CrTiN PVD-coated tools compared to uncoated HSS tools in CNC turning operations on HCHCR D2 steel, utilizing systematic experimental design and precise measurement techniques to assess CR and machining performance [7, 8].

### Statistical analysis

SPSS software, version 23, played a pivotal role in this study, enabling the analysis of CR measurements and the determination of their statistical significance. It facilitated the examination of the independent variable, CMM, to identify significance values between the CrTiN-coated and uncoated tool inserts. Within SPSS, various statistical tests, including equality of means, were conducted to assess the impact of cutting speed, feed rate, and depth of cut (independent variables) on the cylindrical value (dependent variable). Descriptive tables and CMM value tables were employed to comprehensively analyze and present the research findings, following the methodology outlined [9].

## Results

The statistical analysis of this study revealed significant findings. For the uncoated insert group, the mean CR was found to be 1315.8125, with standard deviation values ranging from 349.90070 to 349.90070. In contrast, the standard error mean for the novel PVD-coated CrTiN tool insert was 87.47601, and for the uncoated insert, it was 86.72518. An independent sample T-test was performed, and the results demonstrated a statistically significant difference in CR ($p = 0.000$, both 2-tailed), with $p < 0.05$. Table 1 to table 8 provided comprehensive information about the research, including the chemical composition and physical properties of HCHCR D2 steel, input parameters for machining experiments, and results of independent samples tests. Notably, table 7 presented a comparative analysis of T-test results for the samples machined

**Table 1:** Chemical composition of HCHCR D2.

| Elements | C | Si | CR | Mn | S |
|---|---|---|---|---|---|
| Wt.% | 0.90 - 1.20 | 0.10 - 0.35 | 1.00 - 1.60 | 0.30 - 0.75 | 0.040 max |

**Table 2:** HCHCR D2 steel material of physical properties.

| Physical properties | Value |
|---|---|
| Density | 7.7 × 1000 kg/m$^3$ |
| Melting point | 1421 °C |
| Compressive strength | 862 mpa |
| Poisson's ratio | 0.27 - 0.30 |
| Elastic modulus | 190 - 210 Gpa |

**Table 3:** HCHCR D2 steel material mechanical properties.

| Material name | Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) |
|---|---|---|---|
| HCHCR D2 | 1030 | 862 | 20 |

**Table 4:** Process parameters of CNC turning.

| Levels | Process parameters | | |
|---|---|---|---|
| | Spindle speed (N) (rpm) | Feed (f) (mm/rev) | Depth of cut (mm) |
| 1 | 500 | 0.05 | 0.25 |
| 2 | 750 | 0.75 | 0.5 |
| 3 | 1000 | 0.1 | 0.75 |
| 4 | 1250 | 0.125 | 1 |

**Table 5:** Experimental observations of input and output responses of coated inserts.

| Trial no. | Spindle speed (N) (rpm) | Feed ( f ) (mm/rev) | Depth of cut (mm) | CR (mm) |
|---|---|---|---|---|
| 1 | 500 | 0.050 | 0.25 | 0.023 |
| 2 | 500 | 0.750 | 0.50 | 0.007 |
| 3 | 500 | 0.100 | 0.75 | 0.011 |
| 4 | 500 | 0.125 | 1.00 | 0.030 |
| 5 | 750 | 0.050 | 0.50 | 0.032 |
| 6 | 750 | 0.750 | 0.25 | 0.026 |
| 7 | 750 | 0.100 | 1.00 | 0.021 |
| 8 | 750 | 0.125 | 0.75 | 0.056 |
| 9 | 1000 | 0.050 | 0.75 | 0.042 |
| 10 | 1000 | 0.750 | 1.00 | 0.030 |
| 11 | 1000 | 0.100 | 0.25 | 0.018 |
| 12 | 1000 | 0.125 | 0.50 | 0.009 |
| 13 | 1250 | 0.050 | 1.00 | 0.019 |
| 14 | 1250 | 0.750 | 0.75 | 0.018 |
| 15 | 1250 | 0.100 | 0.50 | 0.049 |
| 16 | 1250 | 0.125 | 0.25 | 0.022 |

**Table 6:** Experimental observations of input and output responses (CR) of uncoated inserts.

| Trial no. | Spindle speed (N) (rpm) | Feed ( f ) (mm/rev) | Depth of cut (mm) | CR (mm) |
|---|---|---|---|---|
| 1 | 500 | 0.050 | 0.25 | 0.019 |
| 2 | 500 | 0.750 | 0.50 | 0.038 |
| 3 | 500 | 0.100 | 0.75 | 0.018 |
| 4 | 500 | 0.125 | 1.00 | 0.014 |
| 5 | 750 | 0.050 | 0.50 | 0.051 |
| 6 | 750 | 0.750 | 0.25 | 0.018 |
| 7 | 750 | 0.100 | 1.00 | 0.032 |
| 8 | 750 | 0.125 | 0.75 | 0.016 |
| 9 | 1000 | 0.050 | 0.75 | 0.023 |
| 10 | 1000 | 0.750 | 1.00 | 0.030 |
| 11 | 1000 | 0.100 | 0.25 | 0.026 |
| 12 | 1000 | 0.125 | 0.50 | 0.013 |
| 13 | 1250 | 0.050 | 1.00 | 0.021 |
| 14 | 1250 | 0.750 | 0.75 | 0.014 |
| 15 | 1250 | 0.100 | 0.50 | 0.023 |
| 16 | 1250 | 0.125 | 0.25 | 0.171 |

with both types of tool inserts, reinforcing the statistically significant findings.

The experimental setup and machinery were described in figure 1, showcasing the CNC turning machine center specifications. Figure 2 depicted specimen samples used for measuring CNC CR in both the control and experimental groups. Figure 3 illustrated the CMM machine Daisy 564 employed for testing cylindrical values in all 32 samples, ensuring precise and consistent measurements. Lastly, figure 4 displayed G-graphs generated from the independent samples test results, visually representing the significant differences in CR observations. Overall, this study's rigorous statistical analysis and comprehensive experimental setup have provided valuable insights into the impact of novel CrTiN PVD-coated tools versus uncoated inserts on CR in CNC machining of HCHCR D2 steel. The statistically significant findings hold significance for improving machining precision and quality in industrial applications.

**Table 7:** Result of T-test for sample HCHCR D2 steel which were machined by two methods. Group A samples are machined by uncoated standard insert and group B samples are machined by novel CrTiN PVD coated insert. The sample means of the proposed method (Group B) significantly gives better cylindrical value than the uncoated insert used in the sample group.

| Group statistics | | | | | |
|---|---|---|---|---|---|
| | Group | N | Mean | Std. deviation | Std. error mean |
| CR | A | 16 | 1315.8125 | 349.90403 | 87.47601 |
| | B | 16 | 1315.8125 | 346.90070 | 86.72518 |

## Discussion

When comparing the performance of novel CrTiN-coated HSS tools to uncoated HSS tools, it becomes evident that the former significantly outperforms the latter in terms of CR or ovality. In a study conducted [10], the sample machined with the novel CrTiN-coated tool exhibited the lowest CR, measuring a mere 0.022 mm. In contrast, samples machined with uncoated HSS tools displayed higher CR, with a maximum error reaching 0.042 mm. This remarkable improvement in cylindrical accuracy can be attributed to the novel CrTiN PVD coating applied to the tools. The coated tools demonstrate superior performance in achieving a high-quality cylindrical value on machined components, as highlighted [11]. The feed rate and cutting speed were identified as crucial factors affecting the cylindrical quality of machined components, as emphasized [12].

The influence of material parameters on cutting forces during turning operations on HCHCR D2 steel was also considered. Dry machining, a common practice in CNC machining, requires precise cutting speed and other input parameters. According to SPSS analysis, cutting speed had a lesser impact compared to the feed rate on cutting force evolution. This underscores the importance of optimizing feed rate and other key parameters for achieving superior machining outcomes [13]. It's worth noting that our university has a rich history of success across various disciplines and is committed to conducting high-quality, evidence-based research. This research endeavor is a testament to our dedication to building on this illustrious legacy. Manufacturing HCHCR D2 steel materials

**Table 8:** Results for independent samples test for CNC machining of HCHCR D2 steel machined with uncoated insert (Group 1) and proposed coated novel CrTiN (Group 2). It is observed that on performing, there is a statistically significant difference for CR p = 0.000 (both 2-tailed), p < 0.05.

| | | Levene's test for equality of variance | | T-test for equality of means | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Sig | t | df | Sig (2-tailed) | Mean difference | Std. error difference | 95% confidence interval of the difference | |
| | | | | | | | | | Lower | Upper |
| CR | Equal variances assumed | 1.348 | 0.025 | 0.702 | 30 | 0.000 | 0.0071250 | 0.0101463 | -0.0135965 | 0.0278465 |
| | Equal variances assumed | - | - | 0.702 | 18.853 | 0.000 | 0.0071250 | 0.0101463 | -0.0141227 | 0.0283727 |



**Figure 1:** CNC turning machine center (Specifications: swing carriage - 260 mm, maximum turning diameter - 290 mm, maximum turning length - 400/500 mm, swing bed - 500 mm, max spindle speed - 4000 rpm, no of station - 8, and chuck size - 200/250).



**Figure 2:** Specimen samples done in for CNC CR for measurement.




**Figure 3:** CMM machine daisy 564 is used to test the cylindrical value.

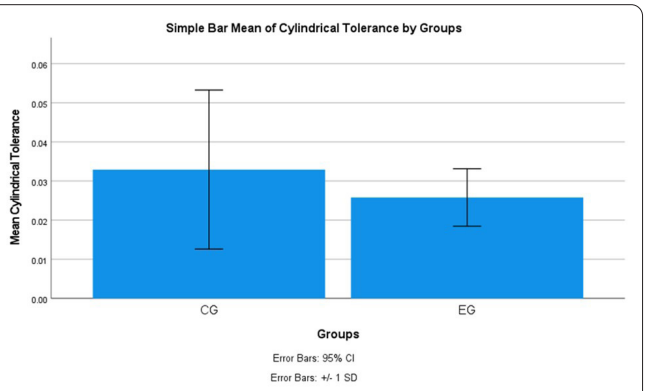


**Figure 4:** Shows the bar graph represented for dominating both PVD coated CrTiN insert and uncoated insert cutters in CR. From these cutters the CrTiN coated insert cutter produced CR even in variation of cutting speed, feed, and depth of cut. X-axis: uncoated and CrTiN coated uncoated tool, Y-axis: mean CR of detection ± 1SD.

is indeed challenging, and CNC machining often necessitates the use of coolants. Despite its modest cutting performance and mechanical strength, the future holds promise for reducing workpiece cylindrical ovality through the application of novel CrTiN-coated tools. In conclusion, the study showcases the remarkable potential of CrTiN-coated HSS tools to enhance cylindrical accuracy in CNC machining operations, offering valuable insights for the machining industry, and re-

inforcing our commitment to advancing research excellence.

## Conclusion

Within the limits of this study and based on the experimental results, this study has demonstrated significant improvements in cylindrical accuracy in CNC turning operations with HCHCR D2 material. The utilization of unique CrTiN PVD-coated tools has led to a substantial reduction in CR compared to uncoated HSS tools, with a remarkable p-value of 0.000 (both 2-tailed), highlighting the statistical significance of these findings. These results underscore the exceptional potential of CrTiN-coated tools in enhancing precision machining. The reduction in CR signifies the ability of these tools to produce components with superior dimensional accuracy and quality. This research reinforces the value of using CrTiN-coated tools in CNC machining processes, offering a cost-effective means of achieving high-precision parts. In conclusion, the study's findings have significant implications for industries that prioritize machining precision and efficiency. The novel CrTiN PVD coating has proven to be a game-changer, setting the stage for enhanced machining capabilities and high-quality component production.

## Acknowledgements

None.

## Conflict of Interest

None.

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