Effects of grinding $\alpha$–$\beta$ Titanium with 3% CNTs in CBN grinding wheel: An Experimental Study

Deborah Serenade Stephen and Prabhu Sethuramalingam
Department of Mechanical Engineering Department, SRM Institute of Science and Technology, Kattankulathur, Chennai, India.

E-mail: deborahs@srmist.edu.in

Abstract. Carbon Nano Tubes (CNTs) have found an immovable niche in the world of manufacturing in the form of reinforcements in composites. Their many advantageous properties have allowed their usage in innumerable ways and this has led to a plethora of innovations in engineering. In advanced manufacturing of very-hard-to-machine materials like titanium, where surface integrity is of prime importance, the presence of multi-walled CNTs even as less as 3% alongside Cubic Boron Nitride (CBN) in grinding wheels, has demonstrated improved surface finish on Titanium alloy (Ti-6Al-4V). This proposed grinding wheel for use on Titanium, reduces surface roughness and improves Material Removal Rate (MRR) on the Titanium work pieces. It also shows slight improvement in the contour of the wheel.

1. Introduction
Grinding is a material removal process that removes material at small rates such that it can be thought of as a finishing process. However, grinding tools with conventional super-abrasive grits like diamond or CBN, face glazing and require periodic dressing – which reduces productive time. It is also a well-established fact that the method of surface finishing used, influences a complex balance of surface roughness and forces generated during machining. They intensely impact the performance of manufactured parts, their life, resistance to stress, fatigue, corrosion and many more. Titanium (Ti) grade 5 is considered the ‘workhorse’ among all Ti grades as this has the desirable properties of both high strength and less weight. Their applications are many owing to their various advantageous mechanical properties and these are hard to machine metals. Hence the work has been carried out on Titanium.

2. Literature Review
Though most of a material’s identity is tied to its bulk properties, its surface properties have been found to play a crucial role as well; and for some applications, these surface properties are of chief importance [1]. You et al. [2] have used CNTs as cutting grains, where the CNTs were epoxy bonded directly in the grinding wheels to withstand high cutting force and temperature. CNTs without chemical treatment or fictionalization gave the best results in the experimentation. Having established the importance of surface finish, it has been a concluded venture to search for various ways to improve it in the grinding of hard-to-machine materials like Titanium. Being the ‘workhorse’ of the Titanium grades, $\alpha$ – $\beta$ Titanium or grade 5 Titanium with a composition of >90% Titanium, 6% Aluminium and 4% Vanadium, has an average hardness of 360BHN [3]. Prior claims and work done on grinding wheels for grinding Titanium show that silicon carbide particles bonded with silicate material was used in grinding wheels, resulting in crack free surfaces but residual stresses...
and changes in microstructure were observed due to the heat generated at the wheel – workpiece interface. [4, 5] This allows further search for improved abrasives.

Current methods have been studied and it was found that CBN wheels are used predominantly in the surface grinding of Titanium, considering their hardness and their thermal properties. Xun et al. [6] have analysed surface burns on grinding Ti alloys and have obtained a threshold temperature for grinding them with cup wheels. To avoid the burns they have proposed a new design of ‘self-inhalation’. This uses a segmented wheel and has reduced the surface temperature by close to 30%.

Ning et al. [7] proposed that dispersion of carbon nanotubes plays a key role in matrix composites. Dispersion activities and mechanism for three kinds of surfactants were tested. It was found that bending strength and fracture toughness improved to 133% and 146% respectively when surfactants were used. Marius Winter, et al. [8] arrived at optimum levels of process parameters offering Pareto-optimal solutions to improve eco friendliness of an internal cylindrical grinding process. Empirical models were formed and various analyses were carried out. Govindhasamy, et al. [9] describes the use of nonlinear autoregressive exogenous model (NARX) to optimize ring grinding process used in the manufacture of Al substrate discs at the Seagate machining facility in North Ireland. Using these techniques, thickness defects of the workpiece was reduced by 50% as compared to other tested models. Prashant J. Pat et al.[10] analyzed MQL based grinding process. Nano fluids with different concentrations were used as cutting fluids and experimented with an EN8 flat plate on a surface grinding machine. Taguchi designs of experiments were used to identify the percentage contribution of each input parameter and Grey Relational multi objective optimization was used for analysis of these results.

Jinglong Sun, et al.[11] established a theoretical model for grinding forces on wafer thinning process, based on the effect of grinding parameters, crystal orientation and radial wafer distance. Large forces caused wafer damage and sub-surface cracks. The existing process was then modified based on the predictive model devised. Bhupendraand Goswami[12] investigated production of black pepper powder, grinding them at different cryogenic temperatures. Excellent results were observed at -40°C and showed that the surface area and roughness have inverse correlation at this temperature. Results showed that surface area and roughness had an inverse correlation.

Reviewing existing literature and using this knowledge, it was found that grinding of hard-to-machine materials like Titanium, Inconel, etc., continue to pose problems with surface integrity as a large amount of heat is generated and the surface integrity is lost. For this work, the percentage of CNT inclusion was fixed as 3% and grinding wheels - one with 3% CNT in CBN, and another wheel without CNT were fabricated. Their properties and grinding effects on Titanium surfaces were comparatively evaluated with changed input parameters and L9 orthogonal array was used to conduct the experiments.

3. Methodology
The following methodology was followed in conducting the experiments.

![Figure 1. Methodology of the Experimental Study.](image)

4. Experimental Setup
The experimental setup includes a hydraulic surface grinding machine (Avro, Coimbatore) with maximum wheel speed limit of 2400rpm. The table can move on both X and Y axes and the wheel can be raised and lowered on the Z axis. Depth of cut and feed can be varied via controls on the surface.
grinding machine. The horizontal table was fitted with a specially designed jig, to hold the Titanium grade 5 (Ti-6Al-4V) work pieces, on top of the Kistler dynamometer, to also record forces generated during grinding. The entire setup is bolted to the horizontal worktable as shown in Figure 2.

The experiments were conducted in a dry condition, without any coolant application in order to investigate effects of CNT. Both the grinding wheels – the commercially available CBN wheel and the experimental 3% CNT incorporated CBN (3% CNT-CBN) wheels, were of the dimensions as in Table 1. Both the CBN and experimental wheels were manufactured by the same commercial wheel manufacturer. This ensured that highest possible considerations were given in maintaining the percentage-by-weight composition of the 3% CNT-CBN grinding wheel.

**Table 1. Dimensions of Grinding Wheels**

| Dimension    | Value in mm |
|--------------|-------------|
| Outer Diameter | 250         |
| Inner Diameter | 76.2        |
| Thickness     | 20          |

The Titanium work pieces were cut from a bigger Titanium block, into cubes with dimensions 25.4 x 25.4 x 25.4 mm each. This was done using a wire Electrical Discharge Machining (EDM), as shown in Figure 3.
Taguchi’s L9 orthogonal array was used to conduct the experiments and experimental runs wereas per the chart drawn up using Minitab software. Nine surfaces were required for each wheel and these were marked as A (1-3) and B (1-3) to denote surfaces ground with the CBN wheel and 3% CNT-CBN wheels respectively. Four surfaces of each cube named a, b, c, and d were marked and used for grinding as shown in Figure 4. Both the wheels were checked for their contour before beginning the experiments. The entire experimentation was conducted for three levels of each factor as shown in Table 2, and was repeated thrice to ensure the correctness of values. The average values of these three runs have been taken to plot both surface roughness and material removal rates. These values are given below in Table 3.

| Factors          | Level 1 | Level 2 | Level 3 |
|------------------|---------|---------|---------|
| Speed (rpm)      | 1800    | 2100    | 2400    |
| Feed (mm/min)    | 0.1     | 0.2     | 0.3     |
| Depth of cut (mm)| 0.01    | 0.02    | 0.03    |

Figure 3. Workpiece wire cut on EDM.

Figure 4. Titanium work pieces ready for grinding.
Table 3. Experimental Values for Ra and MRR for surfaces ground with both CBN and 3%CNT-CBN wheels.

| S.No | Speed (rpm) | Feed (mm/min) | Depth of cut (mm) | Ra CBN (μm) | MRR CBN (gm/min) | Ra 3% CNT-CBN (μm) | MRR 3% CNT-CBN (gm/min) |
|------|-------------|---------------|-------------------|-------------|------------------|---------------------|------------------------|
| 1    | 1800        | 0.1           | 0.01              | 0.5556      | 2.0913           | 0.1123              | 2.0108                 |
| 2    | 1800        | 0.2           | 0.02              | 0.2994      | 1.4503           | 0.1377              | 2.1787                 |
| 3    | 1800        | 0.3           | 0.03              | 0.177       | 1.1674           | 0.0538              | 2.8357                 |
| 4    | 2100        | 0.1           | 0.02              | 0.5902      | 1.4385           | 0.1438              | 1.5113                 |
| 5    | 2100        | 0.2           | 0.03              | 0.3622      | 1.2639           | 0.1996              | 2.1526                 |
| 6    | 2100        | 0.3           | 0.01              | 0.5967      | 0.672            | 0.0838              | 2.9755                 |
| 7    | 2400        | 0.1           | 0.03              | 0.4831      | 0.9126           | 0.1087              | 2.9355                 |
| 8    | 2400        | 0.2           | 0.01              | 0.5471      | 0.4976           | 0.1339              | 2.2                    |
| 9    | 2400        | 0.3           | 0.02              | 0.5161      | 0.998            | 0.1848              | 2.9768                 |

5. Results and Discussion

The experiments were conducted and results tabulated for surface roughness and MRR. Graphs were plotted for Ra and MRR values and the reasons were analysed.

5.1. Comparison of Surface Roughness (Ra) values for CBN and 3% CNT-CBN wheels.

Observing the entire experiment it was observed that an increase in speeds of the grinding wheel caused higher surface roughness values for both wheels. However, even with this trend, the 3%CNT-CBN wheel showed very low surface roughness values and an overall improvement of 48.18% was obtained. This can be seen from Figure 5, which is a comparison of the surface roughness values.

![Comparison of Surface Roughness Values R₃ (μm)](image)

A comparison of the surface roughness (Ra) values has been done by breaking it down for different speeds. It was observed that, at the lowest speed of 1800 rpm, an increase in both feed and depth of cut lowered surface roughness values for both wheels. On changing the wheel speed to 2100 rpm, surface roughness shot up drastically for the CBN wheel for its lowest feed (0.1mm/min) and medium depth of cut (0.02mm). This is owing to the combined effect of increase in both depth of cut and grinding...
speed. The increase of speed from 1800rpm to 2100rpm and further on to 2400rpm shows that it is detrimental to smooth surface finish. An analysis of the factor effects shows that for the commercially bought CBN wheel, the depth of cut had the maximum influence on the surface roughness. This is shown from Figure 6 and 7 which display main factor effect for CBN and 3%CBN-CNT wheel respectively.

Concluding from these we can confidently say that the lower surface roughness values are due to the presence of CNT nano powders in the 3%CNT-CBN wheel which carry away the heat generated at the wheel-workpiece interface. This is due to the excellent thermal conductivity of the CNT nano tubes whose rigidity and other mechanical properties enable it to function as both cutting points and thermal conductors.

![Main Effects Plot for SN ratios for Ra CBN](image1.png)

**Figure 6.** Main factor effect plot of Surface Roughness $R_a$ for CBN wheel.

![Main Effects Plot for SN ratios for Ra 3% CNT-CBN](image2.png)

**Figure 7.** Main factor effect plot of Surface Roughness $R_a$ for 3%CNT-CBN wheel.

5.2. *Comparison of Material Removal rates (MRR) for CBN and 3% CNT-CBN wheels.*

Comparison of the material removal rates showed trends for both wheels as can be seen from Figure 8. For the CBN wheel, the material removal rates showed a gradual decline with increasing speeds and
for the 3% CNT-CBN wheel, while there was an overall increasing trend, the MRR dipped sharply when the speed was increased from 1800rpm to 2100rpm. This is attributed to the lower feed rate of 0.1mm/min and depth of cut 0.02mm, even though the speed was increased. However the MRR quickly improved for increase in feed rate and depth of cut, and an overall improvement of 3.64% was obtained.

![Comparison of MRR Values for CBN and 3% CNT-CBN wheels.](image)

**Figure 8.** Comparison of MRR Values for CBN and 3% CNT-CBN wheels.

The truth of this can be seen from the factor effect plots which show that feed rate has the maximum effect on the MRR for the 3% CNT-CBN wheel. This can be seen from Figures 9 and 10. From Figure 10, it can also be seen that next to feed rate, speed influences MRR most. This change in influencing factors is due to the presence of CNT nano powders which act as cutting edge themselves. This has been supported by various literature reviews which show that CNTs can be used as cutting grains directly along with abrasive grains in the grinding wheel. Their presence enhances material removal, as their rigid strength improves and lengthens the life of the grinding wheel. An overall improvement of 3.64% in the MRR was found on combining 3% CNT along with CBN grains.

![Main factor effect plot of MRR for 3% CNT-CBN wheel.](image)

**Figure 9.** Main factor effect plot of MRR for 3% CNT-CBN wheel.
5.3 Comparison of circularity for both wheels before and after grinding.

The wheel contour of both wheels were checked before and after grinding. This was done in house using a Contura Zeiss Co-ordinate Measuring Machine (CMM) manually. This test was essential, as it gave us an indication of tool wear that took place during dry grinding. Any irregularity in the circularity of the wheels contribute directly to the obtained surface finish of the workpiece.

The figures of the wheel both before and after are included in Figure 11 and 12, and it was found that the circularity of the commercially available CBN wheel before and after grinding was 0.2128µm and 0.1471 µm respectively. The same for the 3%CNT-CBN wheel µm was 0.2093 and 0.1401 µm respectively. The reduction in the after grinding values are due to the wheels becoming smoother after the experiments and the 3%CNT-CBN wheel shows a 5.06% improvement in the contour. This stability is attributed to the presence of CNT as cutting grains in the wheels, thus contributing to structural rigidity and integrity even when exposed to very high temperatures. More tests are required to see if these properties can be improved upon.

Figure 10. Main factor effect plot of MRR for CBN wheel.

Figure 11. Circularity of CBN wheel before and after grinding.
6. Conclusion

From all these experiments, the following points can be seen and they can all be attributed to the enhanced properties of the grinding wheel due to the presence of 3% CNT present along with the CBN abrasive grains in the grinding wheel.

- Surface finish shows an increase of 48.18%
- MRR shows an increase of 3.64%
- A 5.06% difference in roundness values has been observed after grinding.

All these point out that performance of the 3% CNT-CBN wheel is superior to that of the commercially available CBN grinding wheel and it can be commercially used in the grinding of hard materials like Titanium, Inconel, etc. This work can be extended further by studying the influence of other percentages of CNT inclusion to find out optimum performance and enhance grinding characteristics of the wheel.

7. References:

[1] Astakhov VP. 2010 Surface integrity—definition and importance in functional performance. In Surface integrity in machining (pp. 1-35). Springer, London

[2] You J and Gao Y. 2009 A study of carbon nanotubes as cutting grains for nano machining. In Advanced Materials Research (Vol. 76, pp. 502-507). Trans Tech Publications Ltd

[3] http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTP641

[4] Licht R H and Rue CV, Saint-Gobain Abrasives Inc, 1986. Grinding wheel for grinding titanium. U.S. Patent 4,575,384.

[5] Guo G, Liu Z, An Q and Chen M 2011. Experimental investigation on conventional grinding of Ti-6Al-4V using SiC abrasive. The International Journal of Advanced Manufacturing Technology, 57(1-4), pp.135-142

[6] Xun L, Zhitong C and Wuyi C 2011. Suppression of surface burn in grinding of titanium alloy TC4 using a self-inhaling internal cooling wheel. Chinese Journal of Aeronautics, 24, pp.96-101

[7] Ning JW, Zhang JJ, Pan YB and Guo JK 2003. Effect of Surfactants on the properties of carbon nanotube-reinforced SiO2 matrix composites. In Key Engineering Materials 249, pp. 61-64). Trans Tech Publications Ltd

[8] Winter M, Li W, Kara S and Herrmann C 2014. Determining optimal process parameters to increase the eco-efficiency of grinding processes. Journal of Cleaner Production, 66, pp.644-654.
[9] Govindhasamy JJ, McLoone SF, Irwin GW, French JJ and Doyle RP 2005. Neural modelling, control and optimisation of an industrial grinding process. Control Engineering Practice, 13, pp.1243-1258.

[10] Patil PJ and Patil CR 2016. Analysis of process parameters in surface grinding using single objective Taguchi and multi-objective grey relational grade. Perspectives in Science, 8, pp.367-369.

[11] Sun J, Qin F, Chen P and An T 2016. A predictive model of grinding force in silicon wafer self-rotating grinding. International Journal of Machine Tools and Manufacture, 109, pp.74-86.

[12] Ghodki BM and Goswami TK 2016. Effect of grinding temperatures on particle and physicochemical characteristics of black pepper powder. Powder technology, 299, pp.168-177.