Research Article

Optimization of Cutting Parameters during Dry Turning of Austenitic Stainless Steel Using nc-ALTiN/Si₃N₄, TiAlN, and TiN Coated Inserts

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The nc-ALTiN/Si₃N₄, TiAlN, and TiN coating were deposited using lateral rotating cathodes (LARC) technology on TNMG 160404 cemented carbide turning inserts. Ultrafine grain treated cemented carbide substrates were used in case of TiAlN and TiN inserts. The coated inserts were tested for their hardness and compositions were determined by X-ray diffraction studies. The grain structures of coatings were observed using scanning electron microscopy. Dry cutting tests were performed on AISI 304 stainless steel to compare the performances of these coatings in terms of wear and surface finish imparted to workpiece. 3D confocal laser microscope was used to determine the flank wear. Grey relation analysis was carried out to optimize the machining parameters. Studies reveal that nc-ALTiN/Si₃N₄ coating showed the highest hardness of 28 GPa. The coating also shows a dense grain structure. Furthermore, in cutting tests even under severe dry cutting conditions, the wear observed was less than the other two coatings and surface finish imparted to work parts was less than 2 μm by this coating.

1. Introduction

Dry machining is gaining popularity to maintain the safety of the environment. It demands cutting tool with good life, high oxidation, and wear resistance behavior. Coated cemented carbide cutting tools are most suited [1] for such applications. The austenitic stainless steel is one among the “difficult-to-cut” materials which are widely used in chemical and food processing industries where machine parts demand high wear and corrosion resistance. But they suffer from high work hardening effect and poor thermal conductivity and result in rough surface finish and tool wear [2, 3].

Recent widely used “difficult-to-cut” materials are machined by coated cemented carbides of TiAlN group. In particular the coatings of ALTiN/Si₃N₄ have gained attention of industries and researchers worldwide due to their high hardness (above 40 GPa) and wear and oxidation resistance at elevated temperatures [4]. The ALTiN based coatings possess sustaining of heavy loads, increased plasticity, and prevention of adhering to work material. They also form

bilayer at high temperatures which consists of Al-rich top layer and porous rich Ti-oxide layer. Introduction of fourth alloying element into TiAlN, such as Si, forms Si₃N₄ interfacial layer which improves bond of nc-ALTiN which improves thermal stability and acts as diffusion barrier of oxygen atoms [5–7].

Most of the research investigation in this field demonstrates high temperature behavior of ALTiN/Si₃N₄ while studies of machining parameters of these coatings are scarcely reported. Settineri et al. [8] reported dry milling application AISI M2 steel using AlSiCrN and AlSiTiN tools with cutting speed of 150 m/min and feed of 0.050 mm/rev./tooth and observed Cr based coatings performed poorly with higher tool wear. Fernandez Abia et al. [9] report that the surface finish imparted by nc-ALTiN/Si₃N₄ is about less than 2 μm even under worst cutting conditions. Kulkarni et al. [10] optimized the machining parameters for turning of AISI 304 stainless steel using ALTiCrN coated tools and found that optimum surface finish was obtained with speed range of 200–320 m/min. However deposition and use of Cr based

TABLE 1: Cutting parameters chosen for the machining tests.

Sl. number	Parameter	Value
1	Cutting speed (m/min.)	175, 200, 225, 250
2	Feed (mm/rev.)	0.1, 0.3
3	Depth of cut (mm)	1

vapors from coatings are harmful to human respiratory system and Cr6 generated from Cr doped coating can cause skin cancers [11]. The present work deals with study of comparative performance of TiN, TiAlN, and AlTiN/Si₃N₄ coated inserts in turning of AISI 304 stainless steel and optimizing the machining parameters in order to obtain optimum surface finish under dry cutting conditions.

2. Material and Methods

Commercially available K 25 grade TNMG 160404 cemented carbide inserts were coated with TiN, TiAlN, and nc-AlTiN/Si₃N₄ coatings using PLATIT II80 industrial coating unit. Lateral rotating cathodes technology was used to coat the substrates. The substrates were cleaned prior to the deposition of coating using deionized water and deep-dried in oven at about 100°C. A working pressure of 1–1.5 Pa was maintained in the chamber with substrates being biased at –75 V. The current was varied from 80 to 120 A, between both cathodes with a voltage of –20 V. Further details of coating deposition can be found in our previous work [12, 13]. The coated carbide inserts were tested for Vickers microhardness using a digital MATSUZAWA X-7 hardness tester with a load of 0.1 kgf and dwell time of 15 s. X-ray diffraction of the coatings was carried out to analyze different phases using Bruker's D8 advance X-ray diffractometer. Scanning electron microscopy was carried out using Phenom desktop scanning electron microscopy on the fractured specimens of the inserts to determine the grain structure. Cutting tests were carried out using ACE CNC JOBBER XL and the number of experiments was determined using Taguchi's L8 orthogonal array. Speed and feed considered for cutting tests are presented in Table 1. The flank wear in tool was measured using 3D laser confocal microscope after a dry turning of 10 min. Surface roughness of the work parts was measured using Mitutoyo SJ 201 surface roughness tester. Optimization of the machining parameters was carried out using grey relation analysis.

3. Results and Discussions

3.1. Characterization. The nc-AlTiN/Si₃N₄ coating showed the highest hardness of 28 GPa while TiAlN and TiN coatings showed the hardness of 23 and 18 GPa, respectively. The reported range of hardness for nanocomposite based coatings varies between 24 and 28 GPa [5, 14]. The hardness value obtained for TiAlN and TiN systems is similar to values obtained in [15, 16]. The hardness values for nanocomposite however did not reach the super hardness state (about 40 GPa) as discussed by Vepřek et al. in [4, 17, 18].

TABLE 2: Taguchi's L8 orthogonal array.

Speed (m/min.)	Feed (mm/rev.)
175	0.1
175	0.3
200	0.1
200	0.3
225	0.1
225	0.3
250	0.1
250	0.3

X-ray diffraction studies show that TiN coating is rich in fcc-TiN phase and a strong orientation was observed along (111) and (222) plane. For TiAlN coatings the Al atoms were substituted in TiN, to form fcc-TiAlN. Very low signals were observed for c-TiN structure. Also the peak intensity (111) plane is observed in contrast to (200) plane. Both coatings show a FCC crystal structure. For the nc-AlTiN/Si₃N₄ coating both signals for fcc-AlTiN and Si₃N₄ were observed suggesting both crystalline and amorphous phases being present. However some signals for Hex-AlN crystals were also observed with some TiSi compounds. The possible formation of hex-AlN structure is due to the presence of excess of aluminum and formation of silicide compounds may be related to low nitrogen base pressure. All the coatings showed some traces of oxygen being present which is again related to base pressure while depositing the coatings. The presence of oxygen could have possibly deteriorated the hardness of coatings. We refer to [12] for further details. Similar findings are reported in [4, 5, 19–21].

Scanning electron microscopy (SEM) was performed on the fractured samples of all three coatings. Columnar grain structure was observed in case of TiN and TiAlN coatings, while nc-AlTiN/Si₃N₄ showed a dense grain structure with reduced columnar structure. This suggests that addition of Si phase favors the dense grain growth due to the spinodal phase segregation [13]. Figure 1 shows the cross-section images of all the three coated inserts. Grain structures can be easily compared at different magnifications.

3.2. Cutting Tests. AISI 304 stainless steel grade was the chosen work material. The diameter of the work piece was 50 mm and 300 mm in length as per ISO 3685. Dry turning tests were adopted in order to compare the performances of all three coated inserts. Ten minutes of continuous dry turning was performed after which the flank wear was measured using 3D confocal laser microscopy. Surface roughness of the machined parts was measured after turning test. Table 2 shows Taguchi's L8 orthogonal array for the different possible combination of speed and feed.

Figure 2 shows the wear images of all the three types of insert at speed of 250 m/min. and feed of 0.3 mm/rev. Highly oxidized regions can be observed in case of TiN coatings. The wear is uniform in case of other two coatings. Reduced wear is observed in case of nc-AlTiN/Si₃N₄ coating.

FIGURE 1: SEM images of (a) TiN, (b) TiAlN, and (c) nc-AlTiN/Si₃N₄ coatings.

TABLE 3: GRA for TiN coated insert.

Run	Speed	Feed	Flank wear	Υ_i	Surface roughness	Υ_i	AVG	Grade
1	175	0.1	93.333	0.125	2.3	0.125	0.125	1
2	175	0.3	273.84	0.10817635	3.91	0.0658805	0.087028	5
3	200	0.1	98.896	0.12440374	2.29	0.0966064	0.110505	3
4	200	0.3	284.292	0.10733983	4.91	0.0550689	0.081204	6
5	225	0.1	106.719	0.1235748	1.73	0.115175	0.119375	2
6	225	0.3	357.5	0.10182469	5.74	0.0484672	0.075146	7
7	250	0.1	1736.782	0.05173933	1.501	0.125	0.08837	4
8	250	0.3	2414.659	0.04166667	6.87	0.0416667	0.041667	8

3.3. Grey Relation Analysis. Grey relation analysis converts the multiobjective problem into a single objective problem. In the present work low flank wear and low surface roughness were desired; hence the normalization of data was performed between 0 and 1 using

$$X_i^*(k) = \frac{X_{imax} - X_i(k)}{X_{imax}(k) - X_i(k)}, \quad (1)$$

where $X_i^*(k)$ and $X_i(k)$ are normalized and observed data, respectively. Normalization is carried out for each of the

responses. After normalization, the grey relation coefficient is calculated for each response using the formula

$$\zeta_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_i(k) + \zeta \Delta_{\max}}, \quad (2)$$

where $\Delta_i = 1 - X_i(k)$ and $\zeta = 0.5$.

The grey relation grade is then calculated using $\Upsilon_i = 1/m \sum w X \zeta_i(k)$, $w = 1$, and $m = \text{no. trails taken} = 8$.

The highest GRG represents the optimum product quality that can be obtained with minimum flank wear. Tables 3–5 show the grey relation analysis for all the three coated inserts.

FIGURE 2: Wear images of inserts at $V = 250$ m/min. and $f = 0.3$ mm/rev.

TABLE 4: GRA for TiAlN coated insert.

Run	Speed	Feed	Flank wear	γ_i	Surface roughness	γ_i	AVG	Grade
1	175	0.1	0.005	0.125	2.07	0.054844	0.08992	4
2	175	0.3	153.333	0.09618	2.78	0.041667	0.06892	5
3	200	0.1	60.899	0.11171	1.54	0.071793	0.09175	3
4	200	0.3	230.45	0.08619	2.3	0.049747	0.06797	6
5	225	0.1	80.422	0.10802	1.11	0.095817	0.10192	2
6	225	0.3	280.42	0.08075	2.2	0.051842	0.0663	7
7	250	0.1	86.667	0.1069	0.81	0.125	0.11595	1
8	250	0.3	1023.382	0.04167	2.71	0.042678	0.04217	8

TABLE 5: GRA for nc-AlTiN/Si₃N₄ coated insert.

Run	Speed	Feed	Flank wear	γ_i	Surface roughness	γ_i	AVG	Grade
1	175	0.1	0.001	0.125	1.26	0.1575	0.1	4
2	175	0.3	123.33	0.10001	2.34	0.2925	0.07084	5
3	200	0.1	45.455	0.11446	0.96	0.12	0.10544	2
4	200	0.3	150.45	0.0958	2.2	0.275	0.07001	6
5	225	0.1	73.33	0.10883	0.91	0.11375	0.10504	3
6	225	0.3	220.025	0.08646	2.12	0.265	0.06614	7
7	250	0.1	80.455	0.10748	0.72	0.09	0.11624	1
8	250	0.3	987.123	0.04167	1.69	0.21125	0.04927	8

4. Conclusions

From the present study it is found that nc-AlTiN/Si₃N₄ and TiAlN coating provide a good cutting performance over TiN coating. Although the substrates for TiAlN and TiN inserts were ultrafine grain-treated, the nc-AlTiN/Si₃N₄ outperforms other coatings. The performance of inserts is highly dependent on the type of coating and its properties. Optimum surface roughness between 0.09 and 0.81 can be obtained with TiAlN and nc-AlTiN/Si₃N₄ coated inserts by machining AISI 304 stainless steel with a speed of 250 m/min. and feed of 0.1 mm/rev. Apart from these even the wear of the cutting tool is more uniform when compared to TiN at higher speed and feed. TiN coated inserts oxidize very highly

and tool is completely deformed at such conditions. Even under highest speed of 250 m/min. and feed of 0.3 mm/rev. nc-AlTiN/Si₃N₄ coated inserts show surface roughness less than 2 μ m, compared to TiAlN. Thus from the present study it can be concluded that nc-AlTiN/Si₃N₄ coatings prove as potential candidates to machine “hard-to-cut” materials. Further optimization in tool geometry and design can improve the efficiency of the insert with these coatings.

Competing Interests

There is no conflict of interests in the present work carried out. The work carried out is purely for academic purposes and there is no financial gain to the authors by any means.

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