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RESEARCH

Wear Evaluation on Turning Inserts Superficially Modified with Titanium Nitride by HIPIMS

J.A. Muñoz Diaz[a], W. Palomino Marmol[a], I. González Jaimes[a], I. Fernández[b], E.D. V-Niño[c]

[a]*Universidad Industrial de Santander, Bucaramanga, Colombia,*
[b]*Nano4energy, Madrid, Spain,*
[c]*Foundation of Researchers in Science and Technology of Materials, Colombia.*

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Corresponding author:

Ely Dannier V-Niño
Fundación of Researchers in Science and Technology of Materials, Colombia.
E-mail: deydannv@gmail.com

A B S T R A C T

The research aim evaluates the wear resistance of inserts for turning of tungsten carbide (WC), uncoated and coated with titanium nitride through physical vapor deposition (PVD) process by high-power impulse magnetron sputtering (HIPIMS) technique to different concentration of titanium (Ti) and nitrogen (N). The inserts were tested in turning of the grey cast iron of FC300 type at dry finishing conditions. The tips and cutting edges of inserts were analyzed before and later of tests by means of scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDS). The obtained results of inserts wear were analyzed statistically using ANOVA tool, Tukey, and Taylor with the purpose of validating the HIPIMS technique as an alternative process of surface modification of the cutting tools for mechanized of grey cast iron, which material used in the manufacturing of liners and valves seats for gasoline, gas and diesel engines.

1. INTRODUCTION

The companies of manufacture of cutting tools aim to continuously improve the physical and mechanical properties of their tools, which allow them to serve as suppliers to the metalworking industry [1,2]. During its manufacturing processes, it submits the cutting tools to severe machining conditions, high cutting speeds and high temperatures demanded by the need to increase production speeds and reduce costs, causing excessive wear or premature failures of the cutting tools [1-5].

From the incursion in the market until today, the tools of hard metal have been of great use in the processes of manufacture, due to his high hardness and thermal resistance, that in combination with layers of coating increase significantly the service lifetime of the tools [2,6,7]. These improvements have been obtaining from the decrease in the size of the grain in the substrate and the knowledge growing in the different processes of surface modifications [2,7,8].

The knowledge of the different types of wear and the forms of failure of carbide tools has led to the development in recent years of monolayer or multilayer coatings such as TiN, Ti-Si-N, TiN-AlTiN, CrN-TiN, among others, which besides improving the wear resistance also allows to enhance the adhesion of the outermost coating and reduce the generation of heat in the cutting zone [6-17]. Hence, TiN has been coatings extensively studied and very successfully used in cutting tools because it is excellent properties such as high melting point, high thermal conductivity, high hardness and high wear resistance.

The grey cast iron is widely used for the manufacture of cylinder liners and gas compressors of the oil industry, and shirts for gasoline, gas, diesel engines of the automotive industry. Considering that it is a hard material that has particles of lamellar graphite, its machinability is affected by the predictability variations in the surface layer, caused by the soft, hard zones and free ferrite residues located in a random way, producing the excessive wear of the cutting tool and as a result the increase in the costs of the manufacturing process.

The PVD process using the HIPIMS technique is one of the alternatives that are currently studied for the modification of different types of cutting tools with different types of coatings deposited on the surface. Besides, HIPIMS is a process very energetic operating at a temperature higher in comparison with another magnetron sputtering systems, where the deposited layers have more hardness, less roughness (smoother), and with fewer defects than the done by direct current magnetron sputtering (DCMS) and cathodic arc. [8,13,14,18]. This technique allows the use of industrially unconventional deposition materials such as TiAlN, Cr, and CrN, in addition to the traditional coatings such as TiN, obtaining better performance results in the cut made by the tools compared to the depositions made by other PVD techniques [13,19,20], where with the use of multilayer coatings, is obtaining significant increases in the service lifetime of cemented carbide tools compared to monolayer coatings [7,8,14,21,22].

The present work of investigation consists in realizing an experimental model that allows evaluating the wear in turning inserts uncoated and coated with TiN by HIPIMS technique. The inserts were subjected to repetitive tests of external displacement and dry finishing [9,17] of specimens manufactured in grey cast iron type FC300. The coatings deposited using the HIPIMS technique as a surface modification alternative of the turning machining inserts was validated by the statistical analysis ANOVA, TUKEY and Taylor equation [23]. Besides, the surfaces of the inserts, before and after the wear tests, were analyzed by SEM-EDS, where we check that the wear resistance decreases significantly in the TiN coating with less N concentration, according to the nitrogen concentration defined in the phase diagram for this system [24,25].

2. EXPERIMENTAL DETAILS

Commercial turning tools of tungsten carbide without coating, square geometry without breaking-chip, were selected in this research according to recommendations of mechanized for grey iron, ISO 1832 [26] standard. The inserts (Mitsubishi, SPMN 120408 UTi20T) were surface modified through HIPIMS technique to concentrations different from Ti and N. Before of TiN deposition, the surface was coated with a thin film of Ti, as illustrated in Fig. 1.

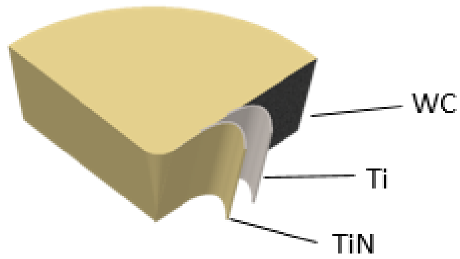


Fig. 1. Coating layers by HIPIMS.

Magnetron sputtering technique by HIPIMS was used for the deposition of both Titanium Nitride layers on the surface of the inserts, where each deposition type depends on concentrations variation of the species present during the process. Before each deposition process, a surface cleaning is performed, by ionic sputtered, in an argon atmosphere (Ar) with a bias voltage of $-600\ V$ during 15 min to a flux of 150 $sccm$. The first TiN coating type was made in an atmosphere abundant of titanium, the flux of Ti between 7 and 9 $sccm$, during 60 min with an average power of 4 Kw, 250 μs pulse time, 150 Hz frequency and substrate temperature approximately to 250 $°C$. The deposition of thin film of titanium, was carried out with a pure metal Ti rectangular target ($200 \times 75\ mm^2$) in argon atmosphere. The Ar working pressure and the magnetron DC power was set to $4 \times 10^{-3}\ mbar$ and $200\ W$ respectively, during $5\ min$ with to a flux of $50\ sccm$. The second TiN coating type was made in an atmosphere abundant of nitrogen, flux of N between 8 and $10s\ ccm$, during $60\ min$ with an average power of $4\ Kw$, $50\ \mu s$ pulse time, $800\ Hz$ frequency and substrate temperature approximately to $250\ °C$. With the purpose of enhancing the adherence between the surface of inserts and TiN coating, a thin film of titanium was deposited during $15\ min$ [27,28].

The material selected for mechanized was the grey cast iron which is denoted as ASTM A48 class 40 or type FC300. In the machining testing, were employed 6 test-probes standardized of $80\ mm$ diameter, $50\ mm$ diametrical limit, $25\ cm$ total length and $20c\ m$ cutting effective length. The cutting length is done stepwise with $20\ cm$ initial length and $60\ °$ cutting angle (Fig. 2).

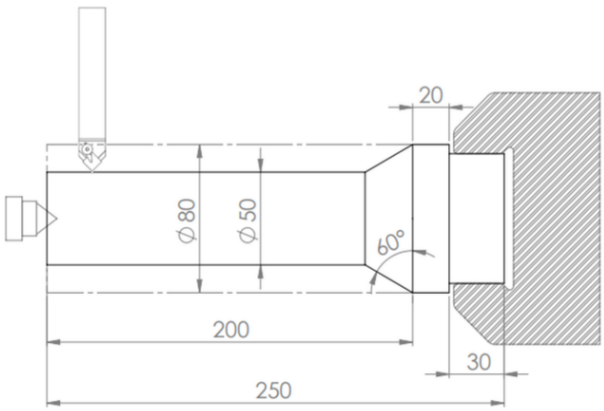


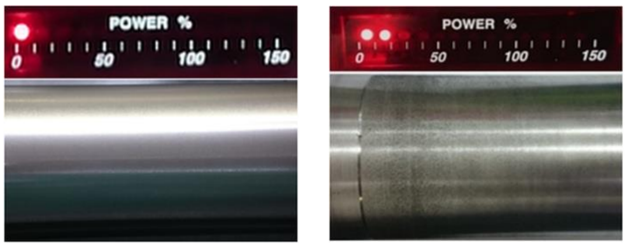
Fig. 2. The geometry of the machining testing by dry finishing turning.

The wear evaluation of inserts by turning of grey cast iron was performed in industrial CNC lathe, EMCO TURN 342, with $300\ mm$ positional ride, $6000\ rpm$ rotation max speed, and Siemens Sinumerik 810 control. The machining testing consisted a process of external displacement with a dry surface finishing of the grey cast iron according to specified parameters in Table 1 [6,9,16,17]. With the purpose of determining to influence of cutting speed on wear and service lifetime of inserts during the mechanized, four cutting speeds were established (Table 1).

The machining by turning testing was performed in dry, without the using cutting refrigerant according to ISO 3685 standard [9,17,23]. Notwithstanding, issues that complicate o disturbs the manufacturing process, such as the buckling effects and vibrations during dry turning were controlled through clamping of workpieces with the gag and center gage. The wear criterion in the inserts uncoated and coated was established according to ISO 3685 standard [23], crater wear criterion, which produces an increase of power factor in a 20% during machining, besides of a change in roughness and piece geometry [9,16,17,23], as illustrated in Fig. 3.

Table 1. Cutting parameters established in the machining testing.

Cutting parameters	Value
Advance speed	$0.1\ mm/rev$
Cutting depth	$0.3\ mm$
Cutting speed 1	$115\ m/min$
Cutting speed 2	$130\ m/min$
Cutting speed 3	$145\ m/min$
Cutting speed 4	$160\ m/min$



(a) (b)

Fig. 3. Power factor in the CNC panel and change surface quality. Power factor increase (a) initial and (b) end.

Figure 3 illustrates the way how the wear was measured from the percentage increase in power. Figure 3a shows an initial condition where the percentage increase of the power factor is of the order of 5 % while at the end of the life of the tool it is of the order of 40 % (Fig. 3b).

3. RESULTS AND DISCUSSION

The removed total volume of grey cast iron during the machining by dry turning to different cutting speeds determine the effectivity of TiN coating deposited on inserts, where coating 1 and coating 2 correspond to the TiN made in Ti and N abundant atmosphere respectively, as is reported in Table 2.

Table 2. Measurement of wear in function removed material.

Speed (m/min)	**Removed total volume (mm^3)**			
	Measure	Uncoated	Coating 1	Coating 2
115	1	90674.248	112948.658	122242.556
	2	87176.117	114321.750	125996.800
	Average	88925.183	113635.203	124119.677
130	1	67133.430	73377.631	87464.717
	2	64940.534	72305.947	84696.973
	Average	66036.982	72841.789	86080.845
145	1	56904.462	67894.112	77708.889
	2	50036.562	71181.443	78836.672
	Average	55470.512	69537.777	78272.780
160	1	37823.205	47614.818	61269.428
	2	40917.388	52574.032	63815.583
	Average	39370.296	50094.455	62542.506

Table 3. Variance analysis, factorial experiment.

Variation font	**Squares sum**	**The degree of freedom**	**Squares mediums**	**F_0**
Surface quality	257838724.9438	2	1285919362.472	300.2488141
Speed	10750996240.2091	3	3583665413.403	836.7486499
Interaction	217188448.9413	6	36198074.824	8.4518745
Error	51394149.2068	12	4282845.767	
Total	13591417563.3011	23		

In Table 3, factorial variance analysis (ANOVA) performed on the material removed in function of standard wear on the inserts according to surface quality (uncoated and coated with TiN) is presented. Where, F_0 is a variable assigned that corresponds to the central statistic, which compares two experimental variances.

Experimental values of F_0 (Table 3) with statistical values, F_t (which allowing establish a decision on whether the F_0 is significant or not, in an experiment); reported by statistical tables for a significance level $\alpha = 0.05$ were compared (Table 4).

Table 4. Statistical values F_0 and F_t.

Variation type	**F_0**	**F_t**
Surface quality	300.2488	3.89
Cutting speed	836.7486	3.49
Interaction	8.4519	3.00

In Table 4 is observed that experimental values (F_0) are greater respect the values statistics (F_t). Therefore, is accepted that at least a surface quality and at least a cutting speed, provide a different result in the wear resistance and the service lifetime of inserts, meaning exists an interaction among these factors.

Figure 4 shows the behavior of the removed material arithmetic means, in function of cutting speed according to the inserts surface quality during turning machining testing, where the range of the errors bars corresponds the max value of the standard deviation obtained from these data.

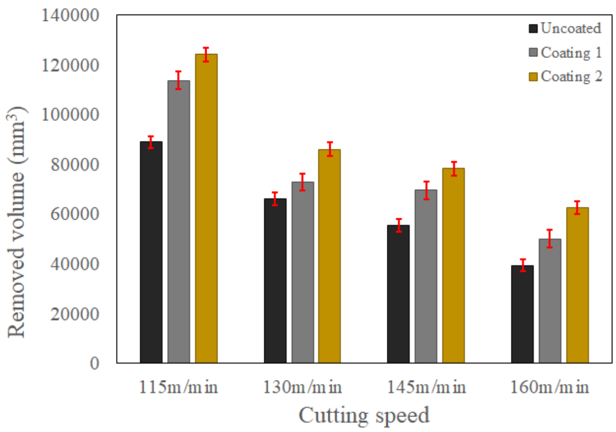


Fig. 4. The behavior of the service lifetime of inserts during the machining by dry finishing turning of grey cast iron.

In Fig. 4, is appreciated that the removed volume and effective service lifetime of the inserts, during turning process of dry finishing of the grey cast iron, increases significantly in the inserts that were deposited with TiN by HIPIMS, presenting an increase in the machining directly proportional to the nitrogen concentration present in the atmosphere during in the surface modification process, and inversely proportional to the cutting speed established the turning machining. The TiN coated inserts in titanium abundant atmosphere, improved in relation to the uncoated in 27.8 %, 10.3 %, 25.4 % and 27.2 % according to the cutting speeds of 115 m/min, 130 m/min, 145 m/min and 160 m/min respectively. While, the TiN coated inserts in nitrogen abundant atmosphere had an increase of service life in comparison with the uncoated of 39.6 %, 30.3 %, 41.1 % and 58.9 %, in the cutting speeds of 115 m/min, 130 m/min, 145 m/min and 160 m/min respectively.

The Tukey multiple comparisons analysis was applied to determine the influence of the surface qualities and the cutting parameters on the service life of the inserts during the turning machining of dry finishing of the grey cast iron.

The Tukey analysis was carried out in the statistical software Minitab 18 and the results obtained with a confidence level of 95 %, are reported in Table 5, where it can be seen that the service life of the inserts is significantly high in the coating of TiN with a high concentration of nitrogen at a machining at speed of 115 m/min, and the least efficient surface quality was that of the uncoated hard metal insert at a high cutting speed of 160 m/min.

Table 5. Results Tukey analysis of factors interaction.

Surface quality	Speed (m/min)	N	Average (mm^3)
Coating 1	115	2	124120
Coating 2	115	2	113635
Uncoated	115	2	88925
Coating 2	130	2	86081
Coating 2	145	2	78273
Coating 1	130	2	72842
Coating 1	145	2	69538
Uncoated	130	2	66037
Coating 2	160	2	62543
Uncoated	145	2	55471
Coating 1	160	2	50094
Uncoated	160	2	39370

The model adjusted to a full quadratic response surface regression in function of the influence of each one of you factors of first, second order and the interactions among those, represented by equation (1).

$$y = \beta_0 + x_1\beta_1 + x_2\beta_2 + \cdots + x_1^2\beta_n + x_1x_2\beta_m + \cdots + x_n^t x_m^t \quad (1)$$

Where, β is the regression coefficient and x_1, x_2, x_n are the factors of first, second order and the interactions among them, which influenced he tests. Consequently, the equation estimated for the response surface regression, obtained in Minitab 18 statistical software, is:

$$Removed\ volume = 565003 + (12651.6 * Surface\ quality) - (6350.74 * Cutting\ speed) + (18.6839 * Cutting\ speed^2) + error \quad (2)$$

In equation (2), the surface quality is categorized according to the type of coating used, then is assigned the values 1, 2 and 3, for the surfaces uncoated, coating 1 and coating 2 respectively.

The behavior of equation (2), corresponding to the response surface in the estimation of removed volume in function surface quality of inserts and cutting speed established during the turning machining dry of the grey cast iron of FC300 type is illustrated in Fig. 5.

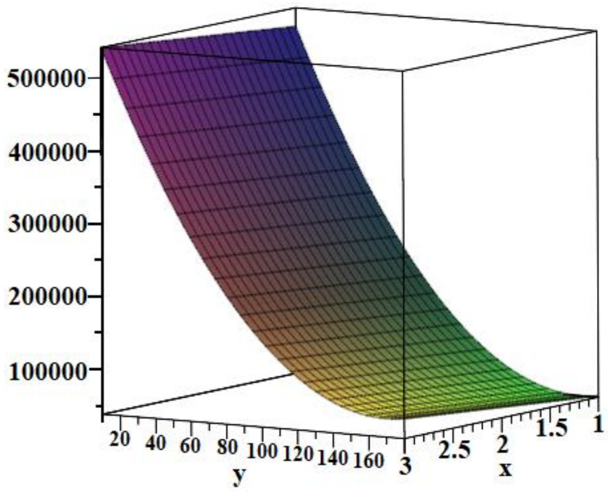


Fig. 5. The experimental behavior of estimated regression surface response.

Figure 5 represents the response surface of the experiment, that is, an estimate of volume removed as a function of the surface quality and cutting speed of the inserts. The model is adjusted to a complete quadratic response surface, depending on the influence of each of its first and second order factors and their interaction. Where the values of x and y correspond to surface quality and cutting speed respectively.

The estimate values, which exhibit a good behavior of the experimental results along of response surface with errors approximately of 10 % max deviation is reported in Table 6, where the parameters such as advance speed, temperature changes during of machining, or external defects, it was not considered during the testing, generating so deviations in statistic estimation applied.

Table 6. Predictions, residuals, and errors of the response surface.

Surface quality	Estimation of response surface				
	Speed (m/min)	Experimental average (mm^3)	Prediction (mm^3)	Residual	Error (%)
uncoated	115	88925.18	94415.4	−5490.22	6.2
uncoated	130	66036.98	67818.0	−1781.02	2.7
uncoated	145	55470.51	49628.4	5842.11	10.5
uncoated	160	39370.29	39846.6	−476.30	1.2
coating 1	115	113635.20	107067.0	6568.20	5.8
coating 1	130	72841.79	80469.6	−7627.81	10.5
coating 1	145	69537.77	62280.0	7257.77	10.4
coating 1	160	50094.42	52498.2	−2403.77	4.8
coating 2	115	124119.68	119718.6	4401.08	3.6
coating 2	130	86080.84	93121.2	−7040.35	8.2
coating 2	145	78272.78	74931.6	3341.18	4.3
coating 2	160	62542.50	65149.8	−2607.29	2

The Taylor equation allow estimating the service life of the inserts in function cutting speed, during the turning machining testing of dry finishing of the grey cast iron, with criteria crater rupture and surface finishing according to roughness grade number type N10-N12 ($R_a = 12.5\mu m - 50\mu m$) [29]. The Taylor equations (3), (4) and (5) corresponding to the service life of the inserts is established by means of the wear critical, which is approximate to $1.2mm$, and of the simple linear regression analysis adjusted by the square minimum method specified in standard ISO 3685 [15]. The inserts lifetime in function of surface quality and cutting speed is reported in Table 7.

Table 7. The service life of the inserts in function of surface quality and the cutting speed.

Speed (m/min)	Service life of the inserts $(minutes)$		
	Uncoated	Coating 1	Coating 2
115	26.28239	32.73874	35.43263
	25.26844	33.13674	36.52081
130	17.21370	18.81478	22.42685
	16.65142	18.53999	21.71717
145	13.08149	15.60784	17.86411
	12.42220	16.36355	18.12337
160	7.879834	9.91975	12.76446
	8.524456	10.95292	13.29491

The Taylor equations (3), (4) and (5), corresponding to the surface quality uncoated, coating 1 and coating 2 respectively, present a good precision, with $0.1\,mm/rev$ advances, $0.3mm$ cutting depth, when using in the cutting tools as criteria of wear the one of the crater rupture, conditions that determine a roughness grade type N10-N12 [29].

$$V_c * T^{0.2965} = 302.235 \quad (3)$$

$$V_c * T^{0.3042} = 328.1708 \quad (4)$$

$$V_c * T^{0.3371} = 379.4644 \quad (5)$$

In Figure 6 is appreciated that Taylor equation is adjust very good and conveniently to real experimental values of the service life effective of the inserts during turning machining of dry finishing of the grey cast iron, with low approximation errors and maxim punctual errors of 4.16 %, 12.38 % and 8.70 % for the surfaces uncoated, coating 1 and coating 2 respectively, for this reason, can be considered as adequate equation that allows estimate the service life of the cutting tools in function cutting speed.

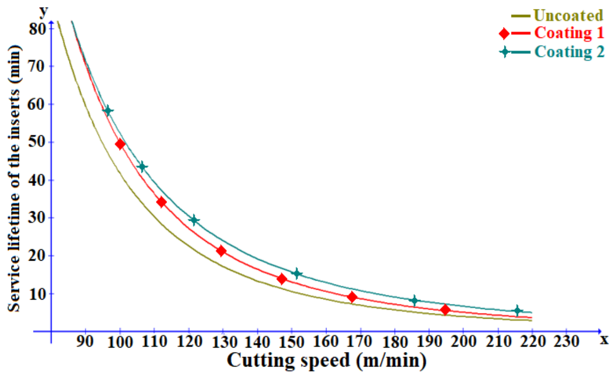
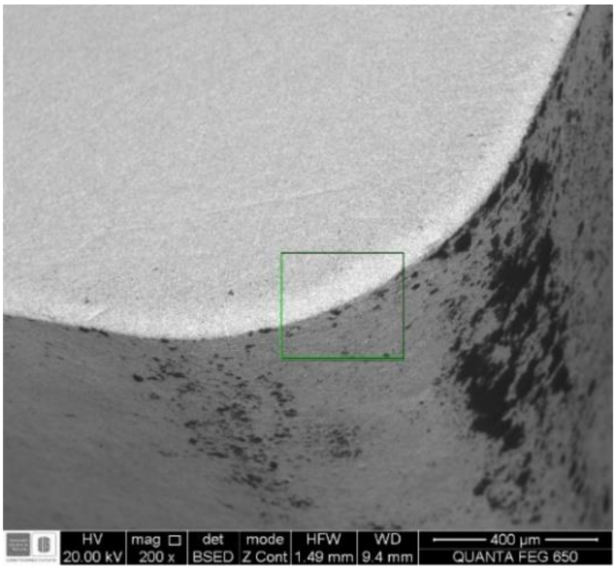


Fig. 6. The behavior of Taylor estimations.

The surfaces of the inserts, before and later of turning machining testing of dry finishing of the grey cast iron, were analyzed through scanning electron microscopy and energy-dispersive x-ray spectroscopy, in scanning electron microscope FEI, QUANTA FEG 650.

Figure 7 shows the photomicrographs, and elemental composition spectrums of insert uncoated before (Figs. 7a and 7c) and after (Figs. 7b and 7d) of turning machining testing, where the surface morphology of the inserts are appreciated. After of the turning machining, is observing that the surface of wear has particles of grey cast iron that adhered during the machining process (Fig. 7b). The EDS spectrums acquired on cutting surface of the inserts before and later of wear are illustrated in Figs. 7c and 7d, where the elements of the material of the turning inserts as such as tungsten (W), titanium (Ti), niobium (Nb), carbon (C), and cobalt (Co) were identified. Besides of the above elements, were detected predominant elements such as iron (Fe) and oxygen (O) that were adhered or increased after turning machining process of the grey cast iron (Table 8).



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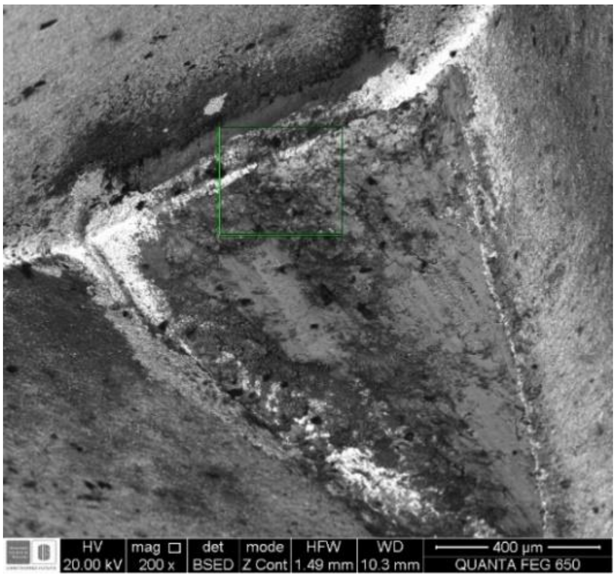

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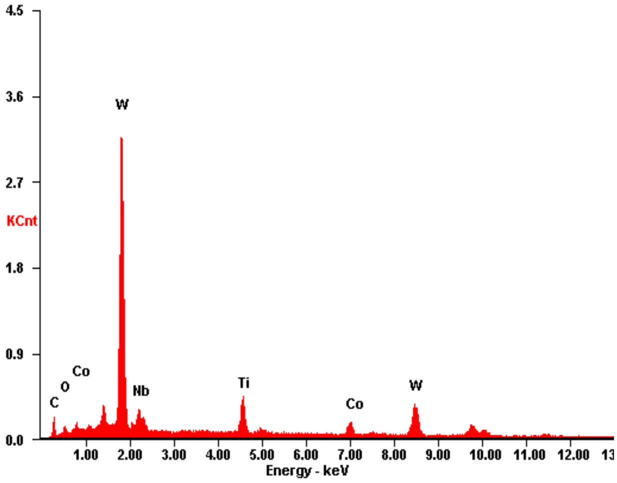

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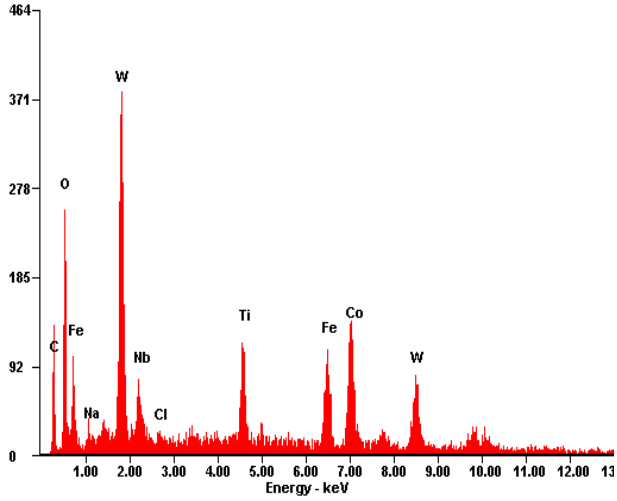
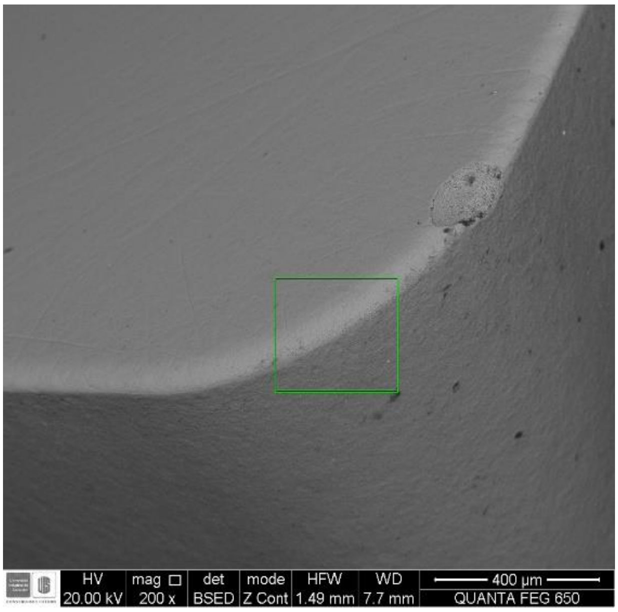


(d)

Fig. 7. Photomicrographs of the insert uncoated, (a) not worn and (b) worn. EDS spectrums on the surface uncoated (c) not worn and (d) worn.

The Figs. 8a and 9a shows the photomicrographs done on surface of the inserts not worn such as for coating 1 and coating 2, where is appreciated a decrease of surface roughness in relation with surface of the inserts uncoated (Fig. 7a), although to a greater magnification is observed that upper and lateral surfaces of the inserts coated having different roughness, with some craters unexpected on cutting edge (Figs. 8a and 9a). The small craters formed could be the cause of the wear increase during the turning machining testing of dry finishing of the grey cast iron, thus, is caused the premature wear and reduction of the coating effectivity. In the photomicrographs of Figs. 7b, 8b and 9b, that were acquired after machining testing on the surfaces uncoated, with coating 1 and coating 2, is observed that the worn region has particles from grey cast iron which were adhered during the machining by turning.



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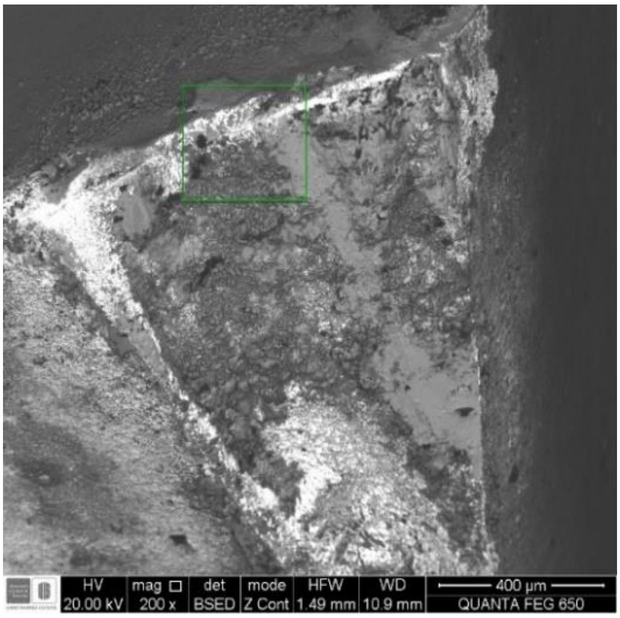

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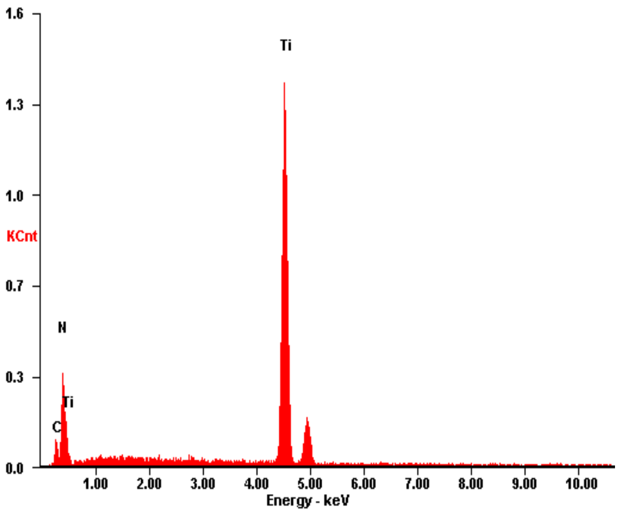

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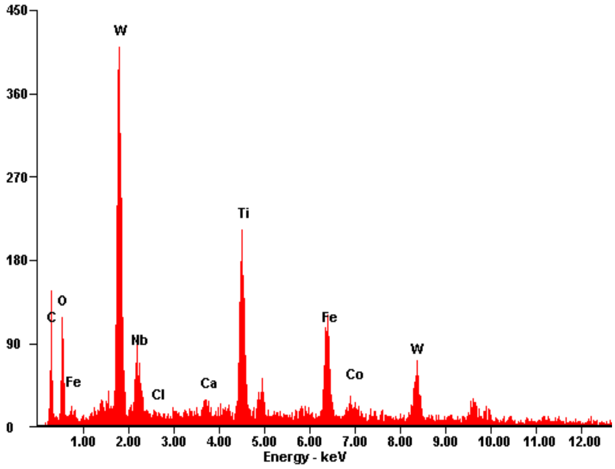
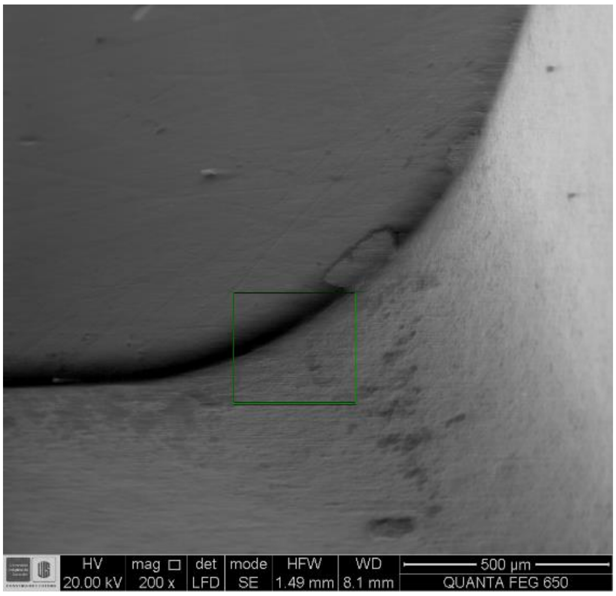
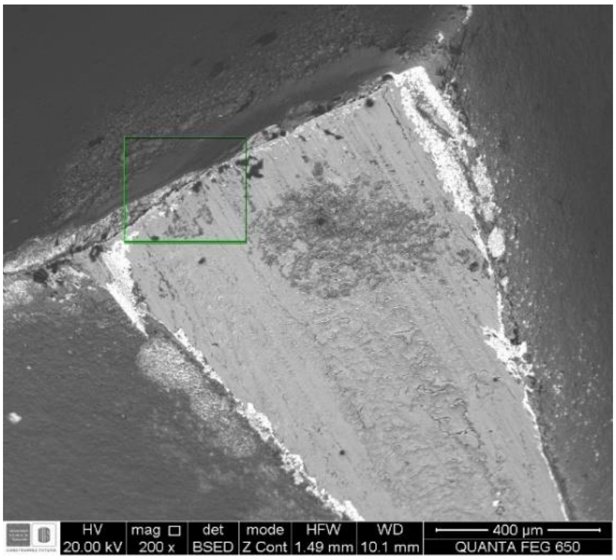


(d)

Fig. 8. Photomicrographs of the insert with coating 1, (a) not worn and (b) worn. EDS spectrums on the surface with coating 1 (c) not worn and (d) worn.



(a)



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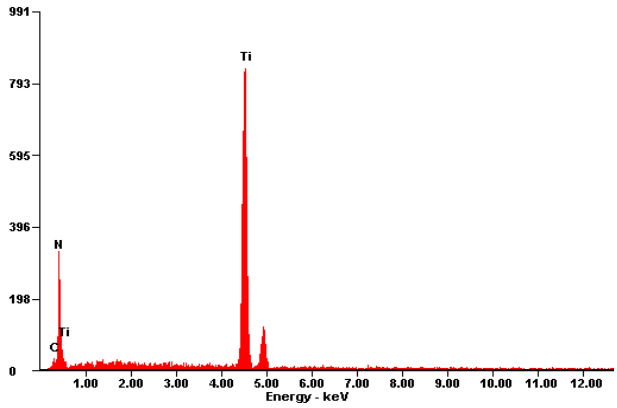

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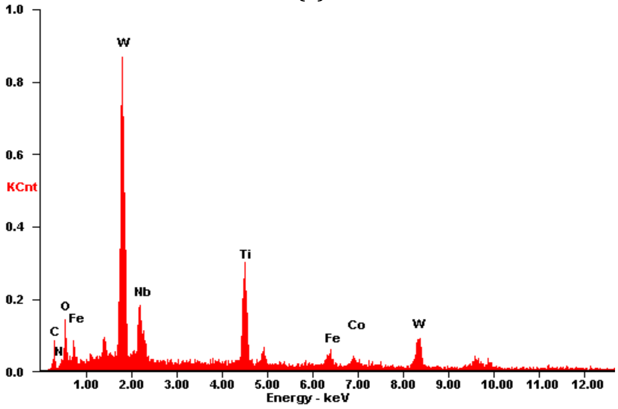

(d)

Fig. 9. Photomicrographs of the insert with coating 2, (a) not worn and (b) worn. EDS spectrums on the surface with coating 2 (c) not worn and (d) worn.

The EDS analysis results for the inserts coated, before and after wear, are illustrated in Figs. 8c, 8d, 9c and 9d and in Table 8 and 9, it shows that before of wear, the main components are Ti and N elements of the coating, and after of wear there is a high content of W, Nb, C, Co, O and Fe element at the surfaces and cutting edge of wear track indicate that the wear mechanism of coating is a mixture of abrasive, diffusive and oxidation wear. In addition, the elemental transfer phenomenon of the workpieces grey cast iron to the surface of the inserts has also been confirmed from the EDS analysis.

The EDS spectrums, acquired on the TiN coating surfaces, before of wear and illustrated in Figs. 8c and 9c and listed in Table 8, inform that the two TiN coating type having concentrations different of titanium and nitrogen, corroborating the established in the experiment, TiN coating made in two different atmosphere types (coating 1: in an atmosphere with titanium high concentration and coating 2: in an atmosphere with nitrogen high concentration).

EDS spectrums obtained on the TiN coating surfaces after of worn are illustrated in Figs. 8d and 9d and listed in Table 9.

Table 8. Detected elements in the spectrum of the inserts surface uncoated and TiN coated before of turning machining testing.

Element	Uncoated		Coating 1		Coating 2	
	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %
C K	6.75	39.34	3.81	10.82	2.97	7.34
O K	2.45	10.73	–	–	–	–
Nb L	7.49	5.64	–	–	–	–
Co K	5.40	6.41	–	–	–	–
W L	70.32	26.78	–	–	–	–
Ti K	7.60	11.10	84.18	59.93	75.24	46.56
N K	–	–	12.01	29.25	21.79	46.11

Table 9. Detected elements in the spectrum of the inserts surface uncoated and TiN coated after of turning machining testing.

Element	Uncoated		Coating 1		Coating 2	
	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %
C K	10.00	31.30	13.15	42.38	7.38	28.14
O K	15.81	37.15	10.03	24.28	10.79	30.88
Na K	0.83	1.36	–	–	–	–
Nb L	4.53	1.83	5.19	2.16	12.81	6.31
Cl K	0.29	0.31	0.14	0.15	–	–
Ca K	–	–	0.79	0.76	–	–
Co K	15.22	9.71	2.41	1.59	2.35	1.83
W L	38.84	7.94	41.82	8.81	45.91	11.43
Fe K	8.75	5.89	13.21	9.15	4.33	3.55
Ti K	5.73	4.50	13.28	10.73	15.48	14.80
N K	–	–	–	–	0.94	3.06

In these analyses species of Fe and O that were adhered or increased during turning machined of dry finishing of the grey cast iron, which is typical of abrasive and diffusive wear were identified. On the other hand, the coating wear of the inserts has also been confirmed from the EDS analysis, where to those elements of the inserts material were identified as such as W, Nb, Co, and C.

The photomicrographs obtaining by scanning electron microscopy validating the good homogeneity and textures of the applied coating, notwithstanding, the small crater formation in laterals face of insert generates a detachment early of the coating and causing a reduction minimum in the effectivity of coating during the turning machining of dry finishing.

4. CONCLUSION

The wear generated by abrasion and thermal diffusion was the more significant in machining, which very possibly caused by high temperatures during the grey cast iron cutting. The inserts coated with TiN presented a good performance during the turning machining of dry finishing due to the homogeny deposition and the good properties of wear resistance that are acquired of species used in the surface modification process.

The inserts coated with TiN in abundant nitrogen atmosphere were the more efficient low the same cutting conditions, and the that removed the greater quantity of material during the turning machining of dry finishing of the grey cast iron, in relation with the inserts modified with TiN in abundant titanium atmosphere and uncoated. The increase of material removed by the coated inserts with titanium nitride in abundant atmosphere of Ti and N in function of cutting speed, having as wear criteria the crater fracture, was off 9.22 % and 39.6 % to 115 m/min, 18.17 % and 30.35 % to 130 m/min, 12.56 % and 41.1 % to 145 m/min, 24.85% and 58.86 % to 160 m/min respectively.

The variance factorial analysis, with a statistical confidence level of 95%, showed that exist an increase significative of the inserts service life coated with TiN in function of removed material, thus validate the coating technique as an alternative for enhancing wear resistance of the cutting tools used in the turning machining processes.

The Taylor reduced equation estimated the service life effective of the inserts, coated and uncoated, in function of cutting speed in the external cylinder processes on the grey cast iron of FC300 type with cutting fixed parameters of 0.1 mm/rev advance and 0.3 mm depth.

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