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Behaviour of PVD coatings in the turning of austenitic stainless steels

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Abstract

The market of turning tools is coped majority by hard metal tools with CVD coating. However, availability of tools with sharp cutting edges is essential in light turning of small parts. In this context, PVD process is optimum for obtaining sharp edges. Therefore, a methodology is presented to evaluate the performance of PVD advanced tools for turning of difficult to machine materials. Four coatings were tested: AlTiSiN (nACo®), AlCrSiN (nACRo®), AlTiN and TiAlCrN. The analysis was developed carrying out wear tests and analyzing different signals such as cutting forces, EDX analysis of inserts, part roughness and insert image analysis. Results indicate that the best coatings for turning of difficult to machine materials as austenitic stainless steels are nACo® and AlTiN coatings, since they offer the best performance. Several factors demonstrate it: better tool flank wear evolution, less tangential cutting force or lower part roughness.

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Keywords: austenitic stainless steel; turning; PVD coating.

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1. Introduction

High productivity and reliability are necessary in today very high competitive context of production. In this context, appropriate selection of cutting geometry and tool material is crucial to be competitive, especially in the field of difficult-to-machine materials, such as stainless steels. Selection of tool coating plays a fundamental role as far as improvement of cutting tool performance is affected directly. As result, in the last years a significant amount of studies has focused in improving coatings with respect to performance, hardness, thermal resistance and low friction coefficients. Nowadays, PVD coatings represent a very important area of study in the scope of nanotechnology and micro-tribology. PVD coatings allow development of nano-composite structures to achieve very high hardness coatings (50 GPa) which even stay stable at high temperatures.

Development of PVD coatings has been focused basically in milling and drilling tools, that is, rotational tools. Settineri et al (2008) analized the wear resistance of AlSiTiN and AlSiCrN nanocomposite coatings for WC mills for high speed. The coated tools were tested in contour milling operation in dry conditions. These tools were coated by cathodic arc PVD with multilayer and gradient microstructure. They were compared to commercial nitride-coated tools. Zitounea et al (2012) compared two types of tungsten carbide drills: with nano-coating and without nano-coating. The results obtained when drilling CFRP and aluminium alloy multimaterial allow conclude that nano-coated drills reduce surface roughness and thrust force.

Nevertheless, the same cannot be said in the scope of turning tools, where market is coped majority by hard metal tools with CVD coating. At the same time, some turning applications require specific tools with optimized geometries and coatings. For example, availability of tools with sharp cutting edges is essential in light turning of small parts; so that, smooth operation is favoured with minimal cutting forces avoiding part deformations and, consequently, dimensional errors. In this case, PVD process is optimum for obtaining sharp edges since coating layers can be applied with few microns thickness over a resistant substrate, which helps to maintain the edge integrity. On the contrary, CVD coatings are featured by rounded edges due to the higher thickness of layers (around 10 μm), what make them inadequate for light turning.

Besides, thickness, thermal properties, residual stresses and grades of adhesion are very different between CVD and PVD coatings. On one hand, PVD coatings provide resistance to wear due to their high hardness. PVD coatings are characterized by compressive stresses which provide tenacity to the edge and improve tool reliability. PVD coatings are recommended when toughness and sharp edge is required simultaneously. Also, these coatings are recommended for machining of sticky materials. Moreover, the use of WC with fine grain size (less than a micron) improves even more the strength of PVD coated sharp edges. On the other hand, CVD coatings are characterized by residual traction stresses and fissures caused by heating, mainly due to the great difference between thermal expansion coefficients for CVD coating and hard metal substrate. Consequently, tools with CVD coatings are more susceptible of reaching a rough border than tools with PVD coating. Prengel et al (2001) studied several advanced PVD coating designs applied by cathodic arc processes or high-ionization magnetron sputtering processes. Results obtained in the milling test indicate that performance of coated tools is function of substrate, coating and macro-geometry and micro-geometry of cutting edge. So, in some manner PVD coatings can be considered more reliable than CVD coatings. In Bouzakis et al (2012) a research is presented about different coating deposition techniques and methods for determining properties such as fatigue, toughness, residual stresses and adhesion of tool coating. These properties are fundamental for performance of cutting tool.So, in some manner PVD coatings can be considered more reliable than CVD coatings.

Keeping in mind the aforementioned, a methodology has been developed that allows to examine the behaviour of the different last generation PVD coatings when machining austenitic stainless steels.

2. Experimental methodology

Four PVD last-generation coatings were analyzed (Fig. 1). Coatings were deposited by means of LARC® technology (Dynamic Lateral Rotating ARC-Cathodes) over a commercial hard metal insert with micrograin quality. The substrate insert was TNMG 160408-23, that is, a hard metal insert of general application adequate for coating deposition, with specific cutting geometry for light and medium turning.

The selected PVD coatings were: AlTiN, AlTiSiN, AlCrSiN, TiAlCrN. These coatings are the most interesting ones at present time, as the state of the art in the field of cutting tools indicates. However, as commented previously, their application to turning tools has not been almost researched.

Liew (2012) evaluates the performance of TiAlN/AlCrN nano-multilayer coated, TiAlN single-layer coated and uncoated carbide tools in low-speed milling under flood and mist lubrication. This work shows that using a nano-coated tool and small quantity of oil a good surface finish with reasonably low tool wear can be obtained. Faga et al (2007) analyzed AlSiTiN nanocomposite coating and compared them with other commercial coated tools. The analysis showed that nanocomposite coating present higher wear resistance at high temperatures and, therefore, this coating is more appropriate for applications where high temperatures are reached, like high speed milling and turning or dry machining. Philippon et al (2011) studied TiAlSiN coating with different silicon content. This work shows that wear resistance is correlated with mechanical properties, and also it is affected by stress state and toughness of coating. Wear rate was reduced by increasing Si content. Also, friction coefficient was independent of Si content. Carvalho et al (2012) also researched wear mechanisms of (Ti,Si,Al)Nx tungsten carbide coated tools to improve the performance of coated tools in dry cutting applications. Veldhuis et al (2009) studied two PVD commercial mono-layered TiAlCrN and experimental nano-multilayered TiAlCrN/WN coatings. This study shows the importance of tribological compatibility within the cutting tool/workpiece system for increasing tool life and improve the surface integrity during end milling of hardened tool steel.

The first coating, AlTiN, contains high percentage of aluminium (>67%) that confers high thermal resistance. This coating has a nano-structure based on TiAlN crystals in a cubic matrix of AlN, very stable at high temperatures, which provides high stability to the cutting edges. Superficial finish of the coating is featured by minimum roughness.

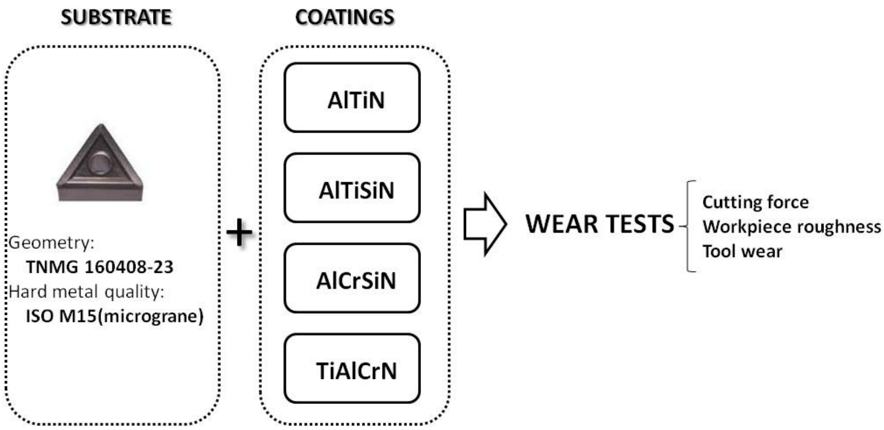


Fig. 1. Scheme used for the analysis of PVD coatings in turning.

The second and third coatings, AlTiSiN (nc-AlTiN)/(a-Si3N4) and AlCrSiN (nc-AlCrN)/(a-Si3N4), are commercially known as nACo® and nACRo®, respectively. These two coatings are also nano-structure coatings with nano-crystalline grains inserted in a silicon nitride matrix. This configuration produces a coating of very compact and high strength structure. The nano-metric size of particles gives high hardness and tenacity simultaneously.

Finally, the TiAlCrN coating improves the properties at high temperatures of conventional coating based on Aluminium-Chromium-Nitrogen.

The performance of coatings was evaluated through wear tests. The operation was a cylindrical turning on a lathe. Each test started using a new edge and ended when tool life criterion was reached or when the edge broke. Recommendations settle down by ISO 3685 standard were considered to define tool life criterion. The material used to perform the tests was AISI 304L austenitic stainless steel with the composition and properties indicated in Table 1. This steel is widely used without improved machinability.

Table 1. Chemical composition and mechanical properties of AISI 304L used in the tests.

Chemical composition												
	%C	%P	%S	%Si	%Mn	%Cr	%Ni	%Mo	%Ti	%N	%Cu	%Fe
AISI 303	0,050	0,033	0,273	0,365	1,776	17,773	8,783	0,271	0,003	0,041	0,273	70,392
AISI 304L	0,024	0,033	0,027	0,240	1,466	17,924	8,208	0,234	0,003	0,065	0,271	71,505

Mechanical properties						
	R_m (N/mm^2)	**R_p 0,2%** (N/mm^2)	**R_p 1%** (N/mm^2)	**Z %**	**A %** %L_sd	**Hardness** HB
AISI 303	638	369	414	53	46	169
AISI 304L	607	313	355	69	48	165

Table 2 shows the properties of the different coatings used in the tests.

Table 2. Properties of PVD coatings used in the tests

Coating	Colour	Hardness (GPa)	Thickness of layer (microns)	Friction coefficient	Maximum Temp. (ºC)
AlTiN	Black	38	1-4	0,3	800
nACo	Violet - blue	45	1 - 4	0,45	1200
nACRo	Blue - gray	42	1 - 7	0,35	1100
TiAlCrN	Blue - gray	34	1 - 4	0,55	900

These machining tests were carried out using the conditions as indicated in Fig. 2. In Fernández–Abia et al.(2011) a similar analysis was done but using high performance conditions; the aim was to study the behaviour of coatings when the concept of economic tool life prevails. The analysis of coating behaviour under these conditions has importance for the own turning operation but also for its extrapolation to other processes. The turning operation is a good characterization process and it permits to extract conclusions to other operations like drilling and milling, where additional factors can mask the results.

Cutting conditions	
f_n (mm/rev)	*0,3*
a_p (mm)	*1,6*
V_c (m/min)	250

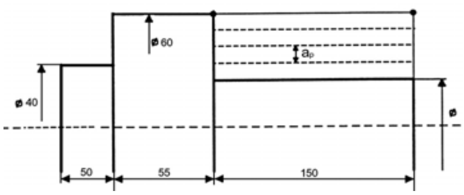


Fig. 2. Cutting conditions and geometry of operation.

During the tests the following factors were controlled:

- The three components of cutting force were registered (Fig. 3).
- The superficial finish was measured (R_a parameter) on the machined parts.
- Wear images were acquired in the tool flank face and height of wear was measured using a graphic application developed with MATLAB. Measurements were acquired each 100 m of spiral cutting length.
- And EDX microanalysis was carried out for the worn tools by means of a sweep electron microscope.

Fig. 3. Mupem lathe with dynamometric plate.

3. Results

Fig. 4 shows the tool flank wear rate with respect to spiral cutting length (SCL) for the series of machining tests at low cutting speeds (250 m/min). It is observed that tool flank wear was less for tools with AlTiN and AlTiSiN (nACo®) coatings. Both tools presented a similar level of wear up to 450 m of SCL. From this value in advance the nACo® coated tool showed smaller wear, reaching a flank wear band width of VB=0,3 mm at 600 m of SCL. The wear associated to the other two tools (AlCrSiN (nACro®) and TiAlCrN) was significantly higher.

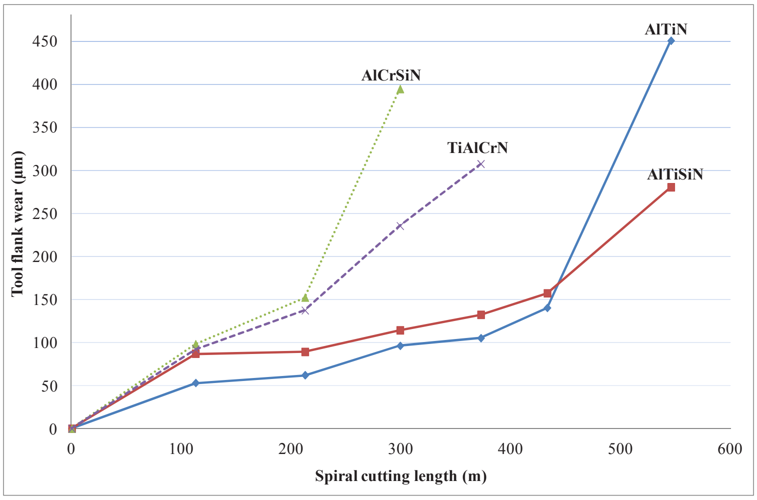
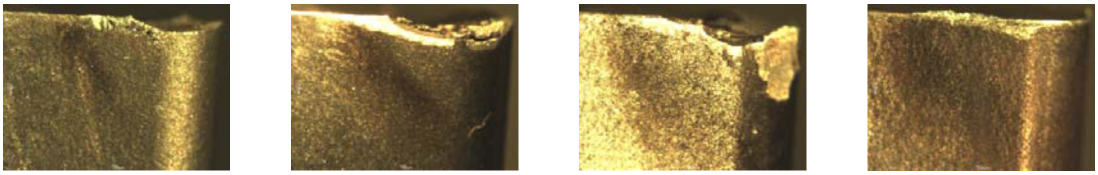


Fig. 4. Evolution of tool flank wear for different PVD coatings as a function of the spiral cutting length (SCL) (V_c=250m/min).

Fig. 5 shows the final condition of the inserts at the end of tests.



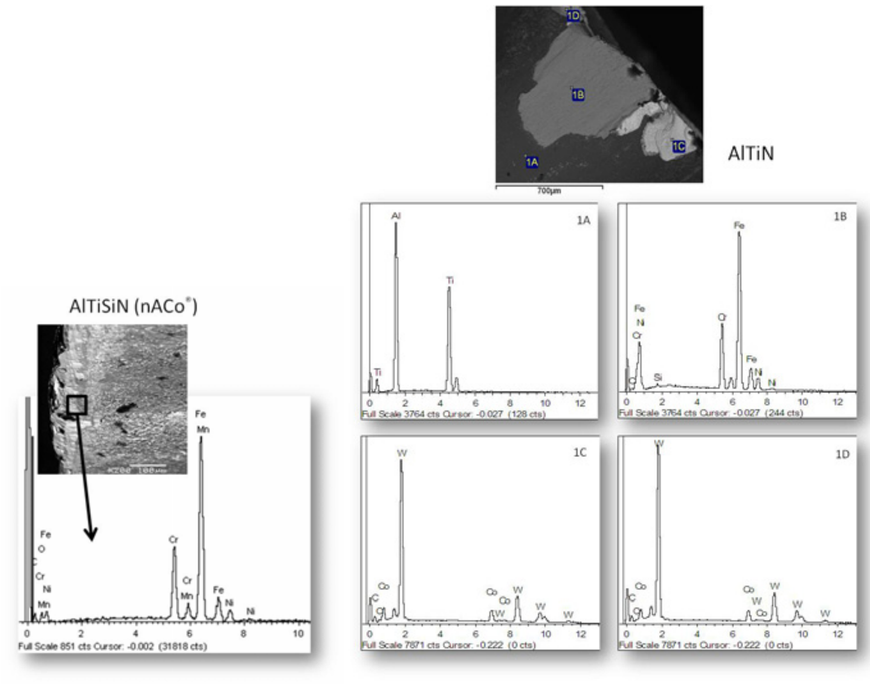
a) b) c) d)

Fig. 5. Condition of inserts at the end of the tests: a) AlCrSiN; b) TiAlCrN; c) AlTiN; d) AlTiSiN.

In order to study the reasons behind the differences in the behaviour of these coatings, scanning electronic microscopy images (SEM) were acquired with a microanalysis EDX of components.

Fig. 6 contains the SEM images for the tools that showed the best behaviour, that is, tools with AlTiSiN (nACo®) and AlTiN coatings. The final condition of the tools can be evaluated clearly in these images. The higher performance for these two coatings with regard to the other two is due to the generation of a protective layer of oxide of aluminium. This layer provides high chemical stability and high thermal resistance. The formation of this layer is favoured by the high content in aluminium that is present in both coatings.

In both cases, some areas are observed with adhered material, but in smaller quantity for the nACo® coating. The nACo coating was superior to AlTiN coating due to its nano-crystalline structure, which favours a quick diffusion of aluminium towards the tool surface, through the grain borders, what speed up the formation of a protective layer which impedes the adhesion of the stainless steel and reduces thermal conductivity. In the image corresponding to the tool with AlTiN coating (Fig. 6b), an area where steel has adhered (area 1B) to the insert is clearly observed, as the microanalysis confirms. In other areas (1C-1D) the steel has also adhered but, later on, it has detached. In the process the coating is also partially detached leaving the substrate unprotected as the EDX microanalysis demonstrates by the high content identified in tungsten and cobalt.



a) b)

Fig. 6. SEM images of tool flank: (a) AlTiSiN (nACo®) coating; (b) AlTiN coating.

With regard to the tools with worse behaviour, that is, AlCrSiN (nACRo®) and TiAlCrN, Fig. 7 shows SEM images of tool flank. These two coatings contain chromium which generates a layer of chromium oxide. This layer has smaller protective capability than the layer of aluminium oxide. Therefore, higher adhesion of stainless steel is observed on tool surfaces. Presence of droplets (Fig. 7a) were observed when using nACRo® coating. Formation of these particles is associated with the evaporation process by electric arc. The existence of these particles is undesirable since sliding of material over the tool surface is more difficult. The EDX microanalysis indicates the existence of stainless steel adhered to edge border (area 1C). In area 1B, far away from the edge border, the steel slid dragging the droplets and causing abrasive wear. On the other hand, a severe adhesion of steel is observed (areas 1B-1C) for the TiAlCrN coating (Fig. 7b) that finally caused edge breaking.

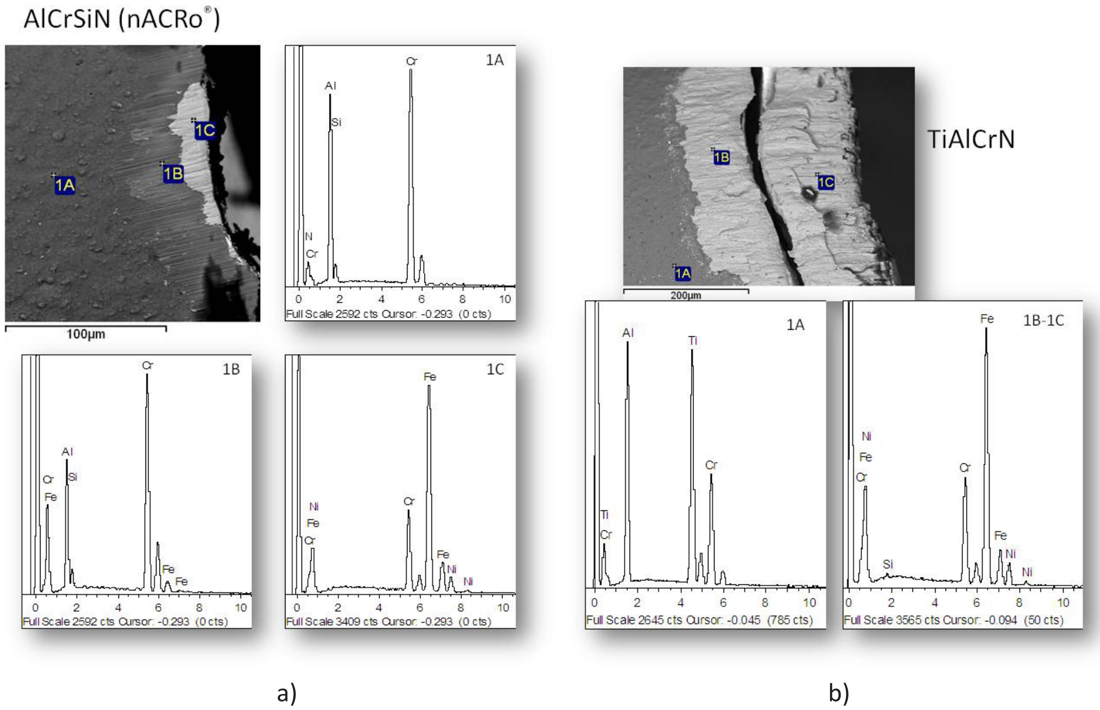
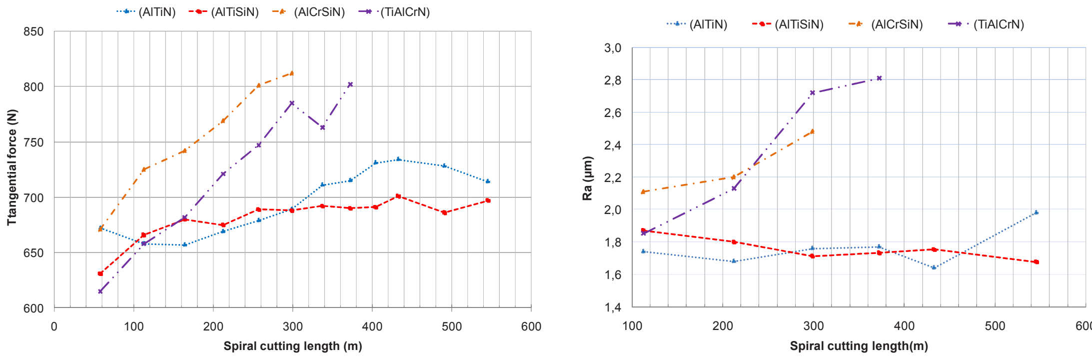


Fig. 7. SEM images of tool flank: (a) AlCrSiN (nACrO®) coating; (b) TiAlCrN coating.

In order to complete the study, the tangential cutting force and the part roughness were analyzed (Fig. 8a). Again, the best performance was also detected for nACo coating. The cutting force keeps almost constant above 300 m of SCL. The AlTiN coating shows a similar behaviour whereas the cutting force for the other two coatings increases continuously, meaning a quick degradation of the tool edge.

R_a roughness values were also lower for surfaces machined using nACo and AlTiN tool coatings (Fig. 8b). Ra values were inferior to 2 µm, even at the final stage of the machining tests. The high tool wear rate experienced by the other coatings (TiAlCrN and nACRo) contributed to increase part roughness quickly.

Taking into account the results obtained in this first stage of machining tests, it can be concluded that AlTiSiN (nACo®) coating offers the best performance for the four tested coatings. In consequence, this coating was used in the second stage of machining tests that analyzes the effect of pre-treatments in the insert performance.



(a) (b)

Fig. 8. Cutting force and part roughness for the different coatings tested at moderate cutting speed (V_c=250 m/min): (a) Tangential force; (b) Ra part roughness.

4. Conclusions

CVD coatings have been studied for long time and optimized geometries have been developed for these types of tool coatings. The same cannot be said with regard to PVD coatings, since PVD process has been applied basically to rotational tools. In processes such as turning, further development is still required. When CVD technology is applied rounded tool edges are used. However, PVD coating is oriented to very sharp edges where high compressive stresses are favourable. Tool geometries designed for CVD coatings are not adequate for PVD coating technology.

Therefore, a methodology has been presented to evaluate the performance of PVD advanced tools for turning of difficult to machine materials. Four coatings were tested: AlTiSiN (nACo®), AlCrSiN (nACRo®), AlTiN and TiAlCrN. Uncoated hard metal tools were not found in the market with the cutting geometry optimized for turning of austenitic stainless steels and with a substrate of enough quality and geometry for PVD coating. However, results can be considered valuable to conclude that the best coatings for turning of difficult to machine materials as austenitic stainless steels are nACo® and AlTiN coatings, since they offer the best performance. Several factors demonstrate it: better tool flank wear evolution, less tangential cutting force which keeps almost constant, lower part roughness with Ra values inferior to 2 µm, even at the final stage of the machining tests. When comparing these two coatings, nACo coating was superior to AlTiN coating due to its nano-crystalline structure, which favours a quick diffusion of aluminium towards the tool surface, through the grain borders, what speed up the formation of a protective layer which impedes the adhesion of the stainless steel and reduces thermal conductivity.

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