A Review of Duplex Treatment Effect on High-Speed Steel Tools

Thermal Conductivity And Roughness Analysis

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***Abstract*— The High-Speed Steel (HSS) is one of the most widely used materials in tools applied to forming and machining operations. The application of duplex treatment showed that can contribute significantly to the optimization of high-speed steel tools, with a careful definition of the nitriding parameters, in addition to the proper choice of coatings and techniques used in deposition. It was observed a negative influence of the roughness increase on the tools performance, processing operations such as polishing were appropriate to mitigate these problems and can be applied to the improvement of surface topography without causing damage to the coating and contribute even more to the performance of these tools. It has been shown that the benefits can be extended to high thermal load applications with the application of low conductivity coatings that begin to be developed and present great efficiency as thermal insulator. This review begins with a brief introduction, followed by a careful review of the implementation of duplex treatments in tools, with emphasis on high-speed steel tools, and the influence of the thermal conductivity and surface roughness on the performance of tools.**

Keywords — duplex treatment; high-speed steel tools; roughness; thermal conductivity.

I. INTRODUCTION

The high-speed steel (HSS) is one of the most important materials for application in machining tools and hot forming operations, with emphasis on rolling, forging and drawing [1,2]. Despite the space occupied by the carbide tools with the increase of cutting speeds in machining process, some operations require considerable tenacity of the tool, which cannot be offered by carbide tools, in such cases the highspeed steels are the best materials. Additionally, the development of surface treatments may contribute to an optimization of HSS's tribological properties, increasing your range of application and contributing to cost reduction in manufacturing operations, since the processing cost of high-speed steel is significantly smaller than that of carbide tools [3–5].

The application of techniques such as Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) allows the deposition of high hardness coatings and good thermal properties. These coatings are composed mainly by Al, Ti, Cr and N, and can contribute significantly to the reduction of wear and consequent increase of tools life [6,7].

The efficiency of coatings deposited by PVD and CVD in tribological applications does not depend exclusively on surface hardness, coatings adhesion is the most decisive aspect and if it is not high enough the coating is easily removed and the deposition takes a negative aspect in the performance of the tools, because the delamination releases abrasive particles of higher hardness than the untreated substrate, contributing to wear increase [8]. The adhesion depends mainly on residual stresses state in the interface and on the relation between the substrate's and coating's properties. A residual stresses state of compression indicates a strong substrate-coating adhesion [9,10]. If the substrate rigidity is much smaller than that of the coating, can occur the defect known as "eggshell", when the deformation of the substrate is too large and does not offer support to the high hardness coating, causing a series of fracture cracks and consequent layer delamination [6,11,12]. In addition, the coating efficiency is influenced by the coatings' thermal conductivity and roughness.

An efficient alternative to improve the adhesion of coatings is the application of plasma nitriding prior to deposition of the coating, combination known as duplex treatment. The nitriding modifies the surface structure through the deposition of nitrides on the surface, forming a hard layer of compounds, and of the diffusion of nitrogen in the substrate (diffusion layer), which consists of a solid solution of nitrogen dissolved in the matrix, the nitrogen concentration decreases with depth of this layer, which results in a similar behavior for the layer hardness [7,13]. Jurci et al. [14] e Rousseau et al. [7] argue that the formation of compounds layer worsens the adhesion conditions of the substrate and that the diffusion layer offers unique properties to the layer adhesion, mainly due to the gradual reduction of hardness in the nucleus direction.

The control of nitriding parameters (temperature, time, pulse duration, etc.), allows to obtain nitreted layers with different properties: absence of compound layer, layer thickness, surface hardness, hardness gradient, etc. [15,16]. Which reinforces the importance of developing studies for optimizing layers, both for nitreted components and for improving adhesion of coatings in components submitted to duplex treatment.

Most of the energy supplied in cutting operations is converted into thermal energy in the cutting region, large portion of this heat is dissipated by the tool, workpiece and chip (cutting residue) [17]. With the growth of dry machining application, given the ecological problems related to the use of cutting fluids, the relation between the tool's and workpiece's thermal conductivity has a decisive role in thermal load directed to the tool. In this context, the application of coatings of low thermal conductivity functions as a thermal barrier and a greater amount of heat is directed to the chip, contributing to a reduction of tools wear [17,18]. The importance of these coatings grows when the tool is used to manufacture components made of low thermal conductivity material, such as titanium and nickel superalloys, used in components such as turbine blades that require a high dimensional accuracy, directly affected by premature wear of tools [19,20].

The study of tools roughness has significant importance in their performance, especially when these tools are submitted to superficial treatments. Fernández-Abia et al. [21] and Puneet, Valleti, and Venu Gopal [8] showed that the reduction in roughness contributes to the reduction of the tools wear. This aspect should be taken into consideration when choosing surface coatings and associated processes. Problems such as the roughness associated with the nature of the coating growth in the PVD and CVD deposition processes modify the surface topography, increasing its superficial roughness [22]. As well as the changes due to the sputtering of the surface on the step of nitriding, in case of application of duplex treatments [23]. Studies aimed at reducing these problems can contribute significantly to enhance the positive effects of the application of duplex treatment.

[23]This paper summarizes the main results of the application of duplex treatment on tools, with emphasis on HSS tools, and discusses the latest studies on the influence of the thermal conductivity and surface roughness on the performance of tools and how these properties can be improved. Although the presence of these properties in tribological studies is not new, the viability of modern applications of high thermal load, as the dry machining and machining of superalloys, depends on these properties, which increase the relevance of studies on this subject. The objectives of this paper are to create a database with relevant information about the improvement of HSS tools through the application of duplex treatment and to encourage scientific research on the application of these tools in high thermal load operations.

II. APPLICATION OF DUPLEX TREATMENT ON TOOLS

The improvement of tools has fundamental importance to increase productivity and quality of products in the metal-mechanical sector. In this context, techniques of Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) allow obtaining high hardness coatings based on Al, Ti, Cr and N, these coatings are being applied to improve the tribological properties and contribute to the reduction of tools wear [6,24]. The studies on the application of plasma nitriding treatment before the deposition (duplex treatment) seek to increase the load capacity of the substrate, improve the transition of hardness and establish a better relation between the properties of the coating and the substrate [6,7,12].

As discussed in this paper, the duplex treatment depends on the characteristics of the nitreted layer. Aspects such as the absence of the layer of compounds and the presence of appropriate hardness gradient are objects of study in order to increase the benefits of the duplex treatment [11,25]. Another important point is the study of the residual stresses state generated in the interface. Results show that residual stresses of compression in the substrate-coating interface are important to establish an adequate strength of adhesion [26].

Tutar et al. [27] showed that the duplex treatment with AlTiN and CrN coating can be used to increase wear resistance by hydro-abrasive erosion in AISI H13 tool steel. The treatments increased the hardness of the samples significantly, reaching its maximum value with duplex treatment of AlTiN, which was equivalent to 15 times the hardness of H13 steel, and the increase with CrN coating was 11 times. The abrasive wear test was done by rotating the sample in a tank with distilled water and abrasive particles of ceramics, the best performance was the sample with CrN duplex, which reduced the loss of mass 2.7 times, while the duplex treatment of AlTiN contributed to a reduction of 2.4 times. The observation of the topography of the worn surfaces showed total pullout of AlTiN coating, while the wear marks of CrN were more punctual, showing that the CrN coating presented better adhesion conditions. Wear rates indicated that the coatings have equivalent performance till a critical time, when AlTiN coating is removed, at this moment the wear rate is increased significantly.

Hawryluk et al. [28] concluded that the application of duplex treatment (especially with Cr/CrN layer) in hot forging tools can contribute to increase the tools life. The study involved characterization in laboratory for comparison between Cr/CrN, Cr/CrN/AlCrTiN and CrN/AlCrN/AlCrTiSiN coatings. The wear test ball-on-disk showed that the Cr/CrN coating presents higher wear resistance at room temperature, on the other hand, in the test at 500 °C the Cr/CrN/AlCrTiN coating had the most satisfying performance. As the temperature is high, the isolated result of wear test would take to the choice of Cr/CrN/AlCrTiN to be applied on the tools, however, other aspects were taken into consideration and justify the choice of Cr/CrN coating, were they: the highest rates Lc1 and Lc2 (which represent the critical loads for wear events), presented in the sliding indentation test, the higher plasticity and uniformity of the Cr/CrN coating (only one with absence of polymetallic nitrides). The duplex treatment with Cr/CrN coating was reproduced on a superior punch of a forging die. The punches with duplex treatment were compared to punches submitted just to plasma nitriding. The analysis of the front surfaces of the nitrided tools showed that shortly after the forging of 2500 parts occurs a deep loss (2 mm depth) of material in an irregular form and spreads to the entire surface. The tool submitted to duplex treatment presented an early stage of low wear, due to the action of the coating, after approximately 6000 workpieces the coating was removed and the wear progressed gradually, reaching a depth of 2 mm after 13000 cycles. The Scanning Electron Microscopy (SEM) results reinforced the bigger protection by the deposited layer of Cr/CrN, it was noted the presence of more stable fissures in these tools, which did not cause immediate damage to the coating adhesion, while the layer was very fragile on the nitrided tools, with the fissures rapidly evolving into cracks and resulting in the total loss of the layer. This behavior was influenced by the excessive tempering presented by the nitrided workpieces.

Paschke et al. [29] showed that the application of duplex treatments with Ti-B-N multilayer coating applied by PECVD (Plasma Enhanced Chemical Vapor Deposition) can be used to decrease the geometric deviation and increase the forging tools life of DIN 1.2343 tool steel. The tool was compared with a plasma nitreted tool and a non-nitreted one, after 10 and 300 forging cycles. In the untreated sample, it was possible to observe the wear phenomena still in the first cycle, through the adhesion of material on the tool, after 300 forging cycles, an considerable plastic deformation was observed in the untreated tool due to the tempering and high tribological load. These mechanisms were not observed in the tools nitreted and submitted to duplex treatment, which showed a protection by part of the nitreted layer and of the coating, respectively. The analysis of the surfaces treated by duplex treatment revealed the formation of fissures on the surfaces after 300 forging cycles, these fissures contributed to adhesion and subsequent pitting corrosion, showing that the treatment alters the tools' wear phenomenon. This phenomenon was responsible for the geometric deviation of the tools even in the absence of plastic deformation, this deviation was considerably reduced in relation to that presented by the untreated tool and represents one of advantages of the treatment because it affects directly the quality of the forged workpieces.

Ebrahimzadeh; Ashrafizadeh [11] studied the influence of duplex treatment application with TiN-TiAlN and TiN-TiAlN-CrAlN coatings on AISI H13 steel for hot forging dies and analyzed the wear at temperatures of 250 °C and 700 °C, which correspond, respectively, at the maximum temperature on the die surface and at the working temperature during the forging of brass. Hot forging tests were also carried out in real working conditions. The results obtained by X-Ray diffraction (XRD) showed the formation of the phase related to TiAlN and, TiAlN and CrAlN phases in the other coating, showing efficiency in deposition. Another important aspect was the non-formation of the compounds layer, proven due to the absence of peaks related to the formation of nitrides, which was also observed in the images obtained by SEM. An increase in surface roughness was observed due to nitriding treatments, the surface of the samples coated with TiN-TiAlN-CrAlN showed roughness greater than in the TiN-TiAlN coating, due to the greater amount of droplets observed in the SEM results. In the pin-on-disk wear tests, the treatments increased considerably the wear resistance in relation to the untreated sample in both the 250 °C and the 750 °C test, with the TiN-AlTiN coating presenting the best results, the coating was not significantly worn, what occurred was a decrease in surface roughness, however in the treatment with TiN-AlTiN-CrTiN the Energy-Dispersive X-ray spectroscopy (EDX) results showed that the coating was completely removed. The duplex treatment with TiN-AlTiN coating was applied in a forging die to evaluate the performance of the tool in service, the untreated die produced approximately 6000 workpieces, while the tool with duplex treatment allowed the production of 18000 workpieces, increasing the tool life by 200%. It was also observed a lower adhesion on the tool surface at the end of its tool life, which contributes positively to the superficial quality of the forged workpieces.

Podgrajšek; Glodež; Ren [30] studied the effects of duplex treatment application with TiAlN coating on hot forging die inserts used in hot forging hammer. The samples were tested in real industrial conditions, performing hot forging with two formation stages, the first with two forging strokes (penultimate cavity of the die) and the second with a forging stroke (last cavity of the die), being the number of operations limited by the dimensional tolerance and the surface finishing required of the forged workpieces. In the end of tool life was observed wear, plastic deformation, cracking and fragmentation of the die's superficial layer, with this wear being critical in the penultimate cavity, due to double of contact time with the workpiece. The metallographic observation by SEM showed the cracking of the surface and coating removal, which are consequences of mechanical and thermal fatigue, were also observed cracks in the tools diffusion zone. The final cavity analysis revealed less intense wear in the last die cavity (submitted to half number of cycles of the penultimate cavity), with few areas of fragmentation. A hardness reduction was observed in the superficial layer, explained by a possible diffusion of nitrogen to the workpiece. As a comparison, a tool submitted only to deposition that in the same service conditions allowed the production of 15000 workpieces and presented a surface free of the presence of fragmentations at the end of the service. The results showed that the improvement of the surface properties is not automatic with the application of duplex treatment and that the service conditions established in the forming with forging hammer were not favorable to the success of the duplex treatment applied, the presence of cracks in the nitreted substrate revealed a deficient coating support that may be related to the substrate tempering due to the various thermal cycles established during the operation. This paper contributes to show that the success of PVD treatment in these applications requires a greater hardening of the substrate with nitriding.

Tan et al. [31] investigated the application of duplex treatment with Ti/AlTiN coating in 40Cr steel used in dies for cold forging. As a parameter of comparison, it was used the monolayer deposition treatment of AlTiN. The Vickers microhardness profile showed the formation of a transitional zone of hardness from the surface to the substrate. The adhesion of the coating was evaluated through the VDI Rockwell C test which classifies the coatings from HF1 to HF12 qualitatively. The limits correspond, respectively, to the conditions of best and worst accession. It was observed an improvement from HF2 to HF1 for coating adhesion when treated by duplex treatment, which contributed, along with the increase of the surface hardness, for the lowest wear rate that was presented by the sample submitted to the duplex treatment. The study of corrosion resistance was a differential in relation to other works applied to tools and showed an increase of corrosion resistance with the duplex treatment.

Çelik; Polat; Atapek [32] proved the efficiency of a duplex treatment with (Cr/AlTi)N compound coating applied in DIN 1.2343 steel, compared with CrN and AlTiN monolayer coatings. The ball-on-disk wear test showed that among the studied coatings the lower friction coefficient (FCO) was presented with the CrN coating to all wear stages. The (Cr/AlTi)N compound coating reduced the relative wear rate at about four times. The difference in wear was confirmed by optical perfilometry tests which showed the (Cr/AlTi)N compound coating preservation, a more severe wear on AlTiN coating and the almost total delamination of CrN coating. The same could be observed in optical microscopy images of the worn surface. In the block-on-cylinder wear test at the temperature of 450 °C was observed a larger FCO for CrN coating, due to the adhesion of aluminum and the formation of the aluminum-aluminum tribe layer. In the transitional and stationary states the oxidation played a leadership role and CrN coating presented the smallest FCO among the studied coatings. The observation of cylinder surfaces (contrast in the wear test) revealed a smoother surface after the test with (Cr/AlTi)N compound coating, showing a higher reduction in the adhesion of aluminum than the observed for the other coatings. The AlTiN coating delayed the aluminum adhesion, therefore, the tribological pair only changed to Al-Al in the last stages of wear, when cracks that were not observed in the (Cr/AlTi)N compound coating appear due to the greater reinforcement offered by the CrN layer. The higher hardness of AlTiN, along with the better adhesion of the compound coating provided by the increasing hardness of the layers, explain the greater wear resistance with compound coating even with lower FCO than the CrN coating.

Tillmann; Dildrop; Sprute [10] studied the influence of nitriding parameters on adhesion of TiAlN and CrAlN coatings on AISI H11 (DIN 1.2343) tool steel substrates. The studied times were 4 h, 8 h, 12 h and 16 h and the flow rates of N2 were 266 sccm, 320 sccm and 400 sccm. It was observed that the increase of nitriding time and the nitrogen flow increases the surface hardness of the samples and the depth of the nitreted layer, thus, the highest hardness was presented by the sample treated at 400 ºC and 16 hours. The scratch test revealed an increase in the critical load Lc3 with application of the duplex treatment in relation to the individual treatment of deposition, this increase was 24% and 65% for the AlTiN and CrTiN coating, respectively, it was also observed a decrease in the scratch width in the samples submitted to duplex treatment. Different wear mechanisms were observed for duplex tools (where the cracks were concentrated in the inner part of the scratch) and for the coated tools submitted to conventional deposition (where the cracks concentrated on the edges of the coating). The performance of the ball-on-disk test showed that the duplex samples showed wear resistance significantly higher than those that did not undergo previous nitriding, the wear coefficient was reduced by up to three and nine times, for the coating of AlTiN and CrTiN, respectively. The increase of nitriding time and of N2 flow contributed significantly to increase wear resistance.

Deng et al. [33] studied the effect of the N2/H2 flow ratio of the nitriding stage in the adhesion of AlTiN coating on AISI-H13 steel. The N2/H2 flow ratios were 50 sccm/25 sccm, 38 sccm/38 sccm and 25 sccm/50 sccm. The roughness results revealed significant differences with the variation in the N2/H2 ratio during nitriding. The analysis of the cross surfaces by SEM revealed the formation of a larger compounds layer for equal quantities of N2 and H2 and a layer almost negligible for higher quantities of H2. The roughness of the AlTiN monolayer coating was lower than all the coatings deposited by duplex treatment, proving that the sputtering during nitriding increases significantly the roughness of the samples, which is reduced subsequently in the coating deposition stage, in accordance with the Volmer-Weber's growth model in which the ions nucleation occurs mainly in the defects created by nitriding. The XRD results confirmed that the compounds layer practically disappears to a richer ratio of H2. The adhesion test by Rockwell C indentation showed the positive influence of the substrate nitriding on the adhesion of the coatings, with all the duplex coatings classified with HF1, while the AlTiN monolayer coating showed adhesion pattern between HF3 and HF4, the nitreted sample with the highest quantity of H2 presented the best result, followed by the sample with the highest quantity of N2 and finally by the nitreted sample with equal quantities of N_2 and H_2, which proved that the increase of the compounds layer impairs the adhesion of the coatings. Similar behavior was observed in the measurement of critical load in the scratch test. Regarding the tribological properties, the coating with the highest quantity of H_2 presented the best result again, with the lowest friction coefficient value. The wear track depth in the duplex coatings was much lower than in the monolayer coating, showing that the higher support and adhesion provided by the nitreted layer contributes significantly to the performance of AISI H13 tools under critical wear conditions.

Atar et al. [25] studied the application of duplex treatment with CrN coating in H13 martensitic tool steel. The microhardness profiles showed a gradual reduction of the hardness towards the center in the duplex sample, in accordance with the change observed in the XRD patterns, where the peak relative to the Fe-α presents an enlargement and a displacement to the left due to the presence of nitrogen as an interstitial element, which proves the formation of the diffusion zone. The XRD analysis also proved the absence of compounds layer since there was no occurrence of characteristic peaks of nitrides, these conditions are essential to improve the adhesion of the coating. The scratch test showed a critical load for the duplex coating exceeding more than two times the critical load in the sample with conventional deposition. The wear rate observed in the sample treated by duplex was four times smaller than the sample submitted only to conventional deposition.

Both et al. [34] studied the application of duplex treatments with TiCN and AlCrN coatings in DIN X100CrMoV8-1-1 cold working tools. The depth profile of the nitrogen obtained by Glow Discharge Optical Emission Spectroscopy (GDOES) revealed the formation of a diffusion layer. By the metallographic images it was not possible to observe the formation of a compounds layer, however, the XRD results presented peaks relative to the Fe_4N, suggesting the beginning of a compounds layer formation and reinforcing the importance of the technique for layer detection. A significant increase in the samples roughness was observed shortly after nitriding, which was even higher after deposition. When compared to the roughness of the simple coatings the roughness presented in the samples treated by duplex was lower, this may be associated with higher resistance of the nitreted substrate to sputtering, which is usually applied for samples cleaning. When comparing the two coatings, AlCrN presented a lower roughness than the TiCN coating. Regarding to hardness, no significant differences were presented between the coatings applied by duplex and those deposited on the substrate without nitriding. The results of Rockwell C indentation test showed that deposition on non-nitreted substrates exhibits fissures and cracks close to indentation and the coating adhesion was classified as HF3, in the duplex samples were observed only radial fissures that do not cause loss of adhesion, assigning the classification as HF1. The best wear results in the ball-on-disk test (lower rates) were obtained for the samples coated with TiCN, followed by the samples treated by duplex with TiCN. For presenting better results, the TiCN coating was chosen for application in the industrial tests in punches used for 1070 sheets cutting. After 700 cycles, the untreated tool presented the most severe wear, which was reduced by replacing it with a nitreted tool. The coated tools showed much lower wear and sharpening preservation, especially in the sample treated by duplex, in which no removal of the coating was observed, in contrast to the simply coated sample, which presented loss of coating on the edges. This behavior proves the importance of the best load support provided by the nitreted layer.

Jurci et al. [14] analyzed the performance of duplex coatings of Cr-N in cold working tool steel. Two nitriding conditions (500 °C for 60 min and 530 °C for 120 min) were tested. The treatment at lower temperatures and shorter time resulted in a nitreted layer free of compound zones, representing a significant advantage in relation to the treatment at 530 °C and which was proven in the scratch test, through the increase of the coating's critical load that surpassed around four times the samples with simple coating. The tool without superficial treatment allowed the fabrication of only 3100 workpieces. With nitriding treatment the production increased to 46 thousand, this yield was expanded to 65 thousand workpieces with the application of duplex treatment with Cr_2N, showing that the coatings application on a nitreted layer free from the compounds layer contributes to improve the performance of the tools.

The HSS is widely used in cutting tools, being the best option for operations that require high toughness, such as deep-hole drilling operations and machining of small diameter hole. With the increase of cutting speeds in industrial processes, the cutting edge wear and the low wear resistance by adhesion limit, in a certain way, the application of HSS on tools [4,5,35]. The application of duplex treatment in these steels has been an alternative to increase their wear resistance and its study can contribute to the expansion of its use in industrial processes and to reduce production costs, because its processing cost is lower than that of the carbide tools. [4,5].

Braic et al. [36] studied the characteristics of a multicomponent hard coating, called (Ti, Cr, Nb) CN, obtained by cathodic arch deposition using two cathodes constituted, respectively, by (Ti 85% Nb 15%) and Cr. The deposition was preceded by nitriding treatment at temperatures of 480 ºC and 510 ºC. The nitreted layers were characterized by depth of microhardness profiles, which revealed the obtaining of thicker surfaces in the treatment at 480 ºC, that was attributed to the highest diffusion rate provided by the increase of the treatment temperature. On the other hand, the treatment at the temperature of 480 ºC produced layers with higher superficial microhardness, due to the slower diffusion, and also a gradual reduction of the hardness at the substrate level, which was not observed in the treatment at 510 ºC. The results of superficial hardness did not reveal significant differences between the coatings applied on the nitreted substrate (duplex treatment) and those applied without nitriding treatment (deposition only). However, in relation to the reference coatings, (Ti, Nb) CN and

CrCN, of the same thickness, a higher surface hardness was observed for the quinternary coating. Among the factors that explain this behavior, the strengthening of the solid solution and the formation of a nanocomposite structure with a large number of phase boundaries stand out. The tribological behavior was evaluated by a pin-on-disk test, all the samples with (Ti, Cr, Nb) CN coating presented lower friction coefficient and lower wear rate when compared to the simply nitreted samples. The best performance, characterized by the lowest wear rate and the lowest friction coefficient, was the sample submitted to duplex treatment with nitriding at the temperature of 480 °C. This result was attributed to the combined effect of surface hardness and the hardness gradient obtained with nitriding. The results showed that the duplex treatment contributes to the improvement of the tribological properties in a more significant way than the isolated nitriding and deposition treatments.

Weirather et al. [37] studied the effects of a duplex treatment performed by Magnetron Sputtering technique for application of Ti1-XAlX coating in high-speed steel - HSS, with nitriding times from 15 min to 60 min. Energy-dispersive X-ray Spectroscopy (EDX) measurements revealed an almost stoichiometric composition of the films, with 49% of nitrogen. The results of roughness tests revealed a decrease in the average superficial roughness (Ra) in all nitriding conditions, which was associated with the preferential removal of roughness species during sputtering, although the average values have been approximately equal, the length of the error bars revealed a more uniform topography for longer nitriding times. To evaluate the adhesion of the coatings was applied Rockwell C adhesion test. The coatings submitted to the duplex treatment were classified with HF2 pattern, while the deposition directly on the substrate presented adhesion limited to HF4, by assigning to the primary nitriding treatment a substantial improvement in the adhesion of the coatings. The ball-on-disk tribological test showed a lower wear rate for the sample nitreted for 30 min, revealing a decrease in wear resistance for higher nitriding times.

Rousseau et al. [7] studied the application of duplex treatment with TiAlN hard coating in HSS drills. In the nitriding stage, the main concern was to avoid the formation of the compounds layer, to ensure a better adhesion of the TiAlN film. The XRD results showed that this condition was reached, because it was not possible to observe the presence of the characteristic peaks of nitrides. It was also observed the displacement of the peak relative to iron, which indicates the increase of the residual compression of the structure due to the presence of nitrogen. The application of the Rockwell C indentation test revealed a greater plastic deformation and delamination points of the film in the samples submitted only to deposition. The investigation of the operational performance of the tools revealed a longer average duplex tools life, exceeding more than twice the tools submitted only to the deposition. The SEM analysis done after the drills performance simulation showed a flank wear (70 μm) that was considerably lower than that presented by the tool submitted only to deposition (300 μm). The film deposited directly on the substrate without nitriding was totally removed and the substrate presented considerable plastic deformation, revealed by the fracture marks, while the tool with duplex treatment did not present significant plastic deformation and no sign of fracture. The results showed the efficiency of the duplex treatments in reducing the plastic deformation of the substrate and delamination of the deposited films and their potential contribution to the increase of tools life.

Kwietniewski et al. [38] studied the application of duplex treatment (nitriding followed by PVD) in HSS tools used in turning operations. The microhardness tests presented higher hardness values in the duplex treatment in relation to TiN monolayer deposition. These values correspond to the compound hardness of the layer and the substrate, evidencing an increase in the static load capacity with the duplex treatment. The XRD results showed a surface without compounds layer and with formation of diffusion zone. The performance test did not present good results for the tools treated by duplex, where only one of the five treated tools reached end-of-life criterion (flank wear of 0.3 mm), the others presented premature fracture of the cutting edge. Tools submitted only to deposition did not show this behavior, evidencing that the edge failure did not occur due to the fragmentation of the TiN layer. The failure was then attributed to the nitreted layer, based on optical microscopy results that showed the formation of a greater thickness diffusion layer at the edges of the tool. Da Silva Rocha et al. [39] e Höck et al.[40] have already shown that nitrited layers with a depth greater than 50 μm can promote an increase of embrittlement and consequently the reduction of wear resistance in HSS tools. The study was important to show that the nitriding condition applied (500 °C and 90 min) should be adjusted to temperatures and/or shorter times, seeking to form a nitreted layer of lower thickness that allows greater stability of the tool during machining.

Hacisalihoglu; Yildiz; Alsaran [4] presented a comparative study of wear on uniquely coated surfaces and surfaces with duplex treatment. The coatings studied were TiN, AlTiN, TiCN e CrN. After the nitriding stage, the XRD result showed the characteristic peaks of iron nitrides, revealing the formation of the compounds layer, however, in relation to the coating, the technique revealed the presence of the characteristics nitrides of each coating. The coatings thickness was 1μm and the nitreted layer thickness was 10μm for the compound zone and 170 μm for the diffusion zone. Among the surfaces submitted only to deposition, just the TiCN film contributed to increase the hardness in relation to M2 high-speed steel without treatment, while the samples submitted to duplex treatment presented higher values of microhardness for all coatings, with emphasis for TiN and TiCN. This behavior was attributed to the support offered by the nitreted layer, responsible for reducing the plastic deformation of the substrate. In the dry wear test, a significant decrease in the friction coefficient was observed in the samples submitted only to deposition, for all coatings, except AlTiN. The nitreted sample presented an increase of the friction coefficient due to the increase of roughness with the treatment, however, in the samples submitted to the duplex treatment, the coefficient of friction increased due to the presence of abrasive particles originated from the delamination of the compounds layer. Under lubricated conditions, the presented friction coefficients were lower than under dry conditions, and no significant differences were presented between samples submitted to duplex treatment and deposition only. The surfaces submitted only to deposition showed the lowest wear volumes, only the one coated with AlTiN presented an increase in the worn volume and the best result was obtained with the CrN coating. On the other hand, the duplex treatment presented a negative result when the coatings used were AlTiN, TiCN and TiN, the only one to present lower loss by wear in relation to the untreated sample was the one coated with CrN, which was still lower than the nitreted one. This can be explained by the low adherence between the compounds layer and the coatings. The results reinforce the importance of avoiding the formation of the compounds layer during the nitriding stage to improve the adhesion on tools and allow a good tribological performance.

Fox-Rabinovich et al. [41] sought to improve the effects of a duplex PVD treatment (TiN layer) by adding an upper layer of anti-friction perfluoropolyether (Z-DOL) to decrease the initial wear of the tools, a critical step in machining using tools with hard coating. The wear process of tools has been studied during turning and milling of a 1040 steel. The friction conditions of the tools were evaluated through the friction adhesion component (main responsible for the catastrophic wear stage of the tools). A reduction in the friction parameter was observed (which relates the shear strength in the tool-workpiece interface with the normal force applied in the test), this reduction was an important aspect for the increase of the tool life, reducing the initial wear, but does not explain alone the increase of 1.5 to 2.0 times in the tools life. The superficial layers were evaluated using Auger Electronic Spectroscopy (AES). The results showed a gradual oxidation of the TiN coating, through the reduction of the nitrogen content and a simultaneous increase in the oxygen content. This behavior was considered beneficial, because the layer containing titanium-based oxygen acts as a barrier of protection of the surface and its formation is related to the passage from the catastrophic stage to the stationary stage of wear. Additionally, the degradation of perfluoropolyether lubricant film (Z-DOL) allows ionic adsorption of fluoride and subsequent formation of titanium fluorides, which by having stronger bonds compared with titanium oxides, are also more stable. Thus, the combined performance of titanium oxides and titanium fluorides considerably increased the protection of the coating and, along with the reduction of the friction parameter, explain the increase in tools life.

Migranov et al. [42] also studied the tribological and wear proprieties of a HSS tool coated with duplex treatment with additional perfluoropolyether coating. The results, similarly to those demonstrated by Fox-Rabinovich et al. [41], confirmed the influence of perfluoropolyether (Z-DOL) in the increase of wear resistance in HSS tools with hard coating, due to the lower value for the friction parameter and the formation of the protective layer of the coating from the formation of titanium oxides and titanium fluorides. The formation of these compounds was proven by the Secondary Ion Mass Spectrometry (SIMS) technique, applied before the beginning of the cutting process and after 200 seconds of cutting, which showed the increase of peaks relative to titanium oxides and titanium fluorides and a reduction of the peak relative to titanium nitride.

III. INFLUENCE OF THERMAL CONDUCTIVITY ON TOOLS PERFORMANCE

Some materials for high temperature applications, such as titanium and nickel based superalloys, present low machinability, one of the reasons is the low thermal conductivity of these alloys [19,43]. As already introduced in this paper, during machining the tools wear is connected directly to the relation between the thermal conductivities of the tool and the manufactured workpieces [18,19]. In coated tools, this effect can be even more significant, because the high temperatures can cause a greater softening of the substrate and consequently the coating delamination [19,20].

Dry machining operations consist of another important high thermal load application, both in the economic and ecological aspects, due to the elimination of cutting fluids. The technical problem associated with dry machining is related to the cutting fluids role in heat dissipation, consequently this heat will be directed to the tool and to the chip, which justifies the importance of lower thermal conductivity values on tools [18,43].

Martan e Beneš [44] studied the thermal conductivity of TiN, TiAlCN, TiAlN, AlTiN, TiAlSiN and CrAlSiN coatings in a temperature range that goes from ambient temperature to 500 °C. The conductivities were measured by the Pulsed Photothermal Radiometry (PPTR) technique. It was observed, for all the coatings studied, an increase of the thermal conductivity with the temperature. The TiAlSiN coating has low thermal conductivity, but increases about 46% when heated to 500 °C, this behavior was similar to that of the TiAlCN coating, but the conductivity of this last is significantly higher. The other coatings presented a lower growth rate, with emphasis on AlTiN, which showed an increase of only 6%, but presented high value. With the addition of Si in the coating (AlTiSiN coating), a nanocomposite structure is formed and the conductivity falls 3 to 4 times. The CrAlSiN coating presented lower thermal conductivity at all temperatures, the result was comparable to multilayer coatings such as AlTiN/Cu, studied by Fox-Rabinovich et al. [45] and discussed in more details in the progress of this paper.

Samani et al. [20] showed that the thermal conductivity of TiN/TiAlN multilayer coatings is lower than that of TiN and TiAlN coatings. The multilayer coatings with number of bilayers equivalent to 5, 10, 25, 50 and 100, were applied on the stainless steel substrate AISI 304, were also deposited individual coatings of TiN and TiAlN. It was observed that the conductivity of TiN films decreases considerably with the addition of AL in its structure (multilayer coatings of TiN/A1Tin). This value decreases from approximately 11.00 W/mK to 4.92 W/mK for the coating with a number of bilayers equivalent to 5 and continues to decrease with the raise in the number of bilayers, reaching 3.25 W/mK for a number of bilayers equivalent to 100. This behavior is related to the columnar structure of TiN which favors the transfer of heat in the crossed plane and is responsible for its high thermal conductivity. It was shown, by the study of XRD results, that the incorporation of Al in the structure of TiN alters the columnar structure, giving rise to a thinner nanostructure, which decreases the conductivity. Additionally, the phonons are the heat carriers in non-metallic crystalline solids and the thermal conductivity increases with the raise of the free path of the phonons [46]. By increasing the number of layers, the density of misaligned displacement increases and the phonons are spread for the interface of the layers, with consequent reduction of their free path, thus, contributing to the reduction of the thermal conductivity of the coating.

Fox-Rabinovich et al. [45] studied the effect of Cu incorporation in AlTiN coating for application in carbide tools used in the turning of 718 Inconel superalloys. Despite the high conductivity of copper, the thermal conductivity results presented a reduction of the conductivity in the multilayer system, which, as discussed above, limits the movement of the phonons and consequently, the heat transfer. In addition to the more favorable heat distribution with the decrease of the thermal conductivity of the coating (higher amount of heat directed to the chip), the introduction of Cu increased the lubricity of the coating, decreasing the friction coefficient, these factors were crucial for the increase of 2.3 times in the lifetime of coated turning tools.

As discussed by Böttger et al. [19], the insulating thermal nature of a multilayers coating is related to its anisotropy, defined as the ratio between the thermal conductivities in the parallel and perpendicular directions to the coating (flow of heat towards the substrate).The authors studied the combination of TiN and AlCrN layers, which presents theoretical anisotropy equivalent to 3, the practical achievement of this relation depends on the deposition of free parallel layers of defects structure. The thermal conductivities were measured in both directions by Time-Domain Thermoreflectance (TDTR) for layers with thicknesses of 50 nm, 125 nm and 250 nm. The results presented a considerable degree of uncertainty, which was associated with localized defects of variation in layer thickness and droplet growth observed in the coating. These defects also justify the values of anisotropy inferior to the theoretical for greater layer thicknesses. The highest anisotropy value was observed for the 50 nm layer, which presented an average equal to the theoretical value. Although the layers of 125 nm and 250 nm presented lower anisotropy values, for all conditions the results were greater than 2, representing the efficiency of the multilayer system proposed in the heat distribution within the coating and confirming its potential for application in cutting tools aimed at high thermal load applications.

IV. INFLUENCE OF SUPERFICIAL ROUGHNESS ON TOOLS PERFORMANCE

Superficial roughness is an important factor for the study of tools behavior, especially when the discussion is focused on coated tools, what includes the tools submitted to duplex treatment. Studies related to the tools roughness indicate a negative influence of the increase of roughness in tools performance [21,43,47]. The application of post-treatments for roughness reduction has improved the performance of coated tools [22,48]. This alternative is of great importance in cases of duplex treatment application, since the sputtering of the surface during plasma nitriding increases the surface roughness of the substrate, which results in an increase in the final roughness, even with the coating application. [23].

Abusuilik [48] evaluated the influence of the superficial roughness on the wear behavior of the AISI H13 steel, varying the roughness of the samples through the application of shot peening treatments, shot blasting followed by micro-blasting, grinding, polishing and plasma nitriding, then AlCrSiN coatings were applied by PVD deposition, the post-deposition roughness measurements showed that the roughness differences were preserved. The coatings adhesion was studied by the scratch test, where the lower Lc3 critical loads were obtained for the coatings with higher surface roughness, associated with the shot blasting and grinding treatments. The less rough surfaces that were submitted to polishing and plasma nitriding followed by polishing, presented higher critical load. The best result presented by the nitreted sample, besides the roughness influence, is due to the support offered by the diffusion layer. The adhesion was also evaluated qualitatively through the Rockwell C adhesion test, in which the worst adhesion condition was HF2, associated with the coating with greater roughness. In the results of the ball-on-disk wear test, the dominant mechanism of wear was the adhesion one, being observed material of the balls in all tools. The type of treatment influenced directly the transfer and accumulation of material, it was observed greater adhesion on the surfaces of higher roughness, associated to pre-treatments of shot peening, shot blasting and grinding. The largest abrasive wear marks observed in the test were in the samples of higher superficial roughness, proving the negative influence of the increase of roughness in the wear resistance of the AISI H13 tool steel.

Do Nascimento Rosa et al. [49] modified the texture of drills producing two different roughness parameters (classified as modified 1 and modified 2) and compared these parameters with the commercial conditions of supply. TiAlN and TiAlCrSiN coatings were applied by PVD deposition process, some samples still were submitted to polishing process after the deposition. The observation of the non-polished tools showed that the coatings slightly increased roughness parameters, with the highest roughness values achieved after TiAlN deposition. In relation to the modification of the surface before deposition, the tools modified 2 always presented higher roughness values in comparison to the modified 1 and the commercial ones, with the lowest roughness values associated with the commercials. After polishing, the roughness of the coated tools decreased and the coated on commercial substrates and modified 1 presented the same average roughness value of the commercial substrate without coating. The measures of interface-surface residual stress revealed the presence of compressive stress with the commercial substrate and tensile stress in the modified substrates. Studies such as Denkena et al. [9] show that compressive stress increases the tools life, revealing a negative aspect with the modification of the surfaces. The performance test revealed a shorter life in the drills modified 2, showing a negative influence of roughness on wear resistance. The high wear resistance of the deposited coatings is partly due to the formation and growth of protective oxides layers, which decrease the friction coefficient and consequently the wear rate, this behaviour of the coatings is discussed in the paper of Zhang et al. [50]. The large peaks shown in the roughness profile of the drills modified 2 do not offer conditions for the growth of the oxide layer, because they are easily plucked in the first stages of wear even with the presence of these oxides. The positive result of the drills modified 1, reinforce the role of roughness in the negative behavior of the modified 2, because the modified 1 also presented residual tensile stresses, which as discussed, are harmful to wear resistance, but the positive aspect of the lower roughness showed a more significant influence on the results.

Saketi e Olsson [22] showed how the increase in coatings roughness influences negatively the initial adhesion of 316L stainless steel in sliding contacts and thus can contribute to accelerate the wear of tools. Different roughness patterns were obtained with the application of grinding, polishing before deposition and polishing after deposition. A CVD process was used to deposit a Ti(C,N)-Al2O3-TiN multilayer system and a PVD process was used to deposit a double-layer coating of (Ti,Al)N-(Al,Cr)2O3. The measures of the friction coefficient revealed the presence of high friction coefficients in all the deposited coatings, including the polished substrates, revealing the influence of the coating morphology on roughness. The post-coating polishing presented a more significant positive impact on the reduction of the friction coefficient. The analysis of the wear track images revealed the presence of stainless steel adhered to the surfaces of the coatings in different patterns and quantities for each of the superficial modifications.[22] The samples submitted only to grinding followed by deposition presented a tendency of large scale transfer of material from the pin to the surface (adhesion). In the coatings deposited post-polishing, no large scale transfer was observed, and the transfer was dominated by irregularities originating from the film's growth. With the polishing of the coatings, the samples submitted to preliminary grinding presented material transfer, which was associated with the remaining irregularities of this process, while those submitted to the polishing pre and post treatment of deposition practically did not present adhesion on the CVD coating and small amounts of stainless steel were transferred to the surface treated by PVD. This adhesion in the polished PVD coating is linked to the presence of micro scale craters that are characteristics of this type of coating.

LIU, C.; LIU, Z.; WANG, B [51] improved the tribological properties of CVD coatings by means of post process of wet micro-blasting. Three commercial multilayer coatings were studied: coating A - TiN(1,2 μm)/Al2O3(5,2 μm)/TiCN(8,5 μm), coating B - Al2O3(5,2 μm)/TiCN(8,5 μm), coating C - Al2O3(2,0 μm)/TiCN(7,0 μm). The coated samples were submitted to wet shot blasting to change their morphology and the roughness reduction was proven for all cases. With the reduction of roughness, the B and C coatings had their wear resistance increased significantly, in dry sliding wear test. In relation to the coating A, the impact of treatment was negative, but it was proven that this does not occur due to reduction of roughness, but by the damage of the TiN layer during shot blasting, which was observed by SEM and EDS results.

Puneet; Valleti; Venu Gopal [8] studied the effect of superficial roughness on adhesion of coatings and consequently in the HSS drills life. The superficial finish of the drills was changed by applying the micro-blasting and drag finishing techniques. The micro-blasted HSS substrates were named MB1 (with Al2O3 - 50 μm), MB2 (with Al2O3 - 15 μm) e MB3 (ZrO2 - 50 μm). The drag polishing was applied in four distinct times and the HSS drills were denoted by ER1 (5 min), ER2 (10 min), ER3 (15 min), ER4 (20 min). In all substrates, PVD coating of TiN was applied. The MB3 treatment produced the smallest superficial roughness, followed by MB2 and MB1. The processes ER1, ER2, ER3, and ER4 resulted in an edge radius of 8 μm, 14 μm, 18 μm, and 20 μm, respectively. To understand the coating effect were simulated uncoated drills that reached maximum limits of 30 to 35 machined holes, were also tested drills coated without any morphology alteration. The results of only 5 machined holes showed a poor adhesion of the coating, causing its delamination and consequent release of abrasive particles responsible for intensifying the wear. [8]With the treatments of micro-blasting MB1, MB2 and MB3, the results achieved were 124 ± 25, 394 ± 10 and 361 ± 15 holes, respectively. The performance of the MB2 drill was similar to MB3, due to the proximity between the roughness values, but the inferior result of the MB1 drill showed the significant influence of the decrease in superficial roughness in the increase of tools life. The evaluation of the evolution of flank wear also presented a better behavior for the MB3 drills (tool of minor roughness). The drag polishing process with the most significant impact was the ER2, which was applied along with the best result of micro-blasting (MB3). The improvement in the performance of the tools was even more expressive, with a total of 810 ± 25 machined holes. This behavior is related to the decrease in the concentration of tensions established at the edge of the tool, resulting in better uniformity of the layer.

Fernández-Abia et al. [21] analyzed the effect of roughness on the application of AlTiSiN coating on carbide tools applied in stainless steel turning. The tools were submitted to micro-blasting and drag grinding to modify the morphology of the surface. The results show lower roughness in the tools treated by drag grinding, therefore, offers better conditions for adhesion of the coating. The Rockwell C adhesion test proved the best support in the substrate submitted to drag grinding, presenting a smaller area of coating detachment. The micro-blasting treatment worsened the adhesion conditions, presenting a larger area of coating detachment in comparison to the tool deposited directly in the substrate. The images of the surfaces after wear tests revealed a regular wear on the tool submitted to drag grinding, proving the good coating adhesion on the substrate. The others presented breakage of the cutting edge. This damage was even more severe in the tool submitted to micro-blasting, which presented high roughness. The paper contributed to show the negative influence of roughness on wear resistance of tools.[48]

V. FINAL CONSIDERATIONS

In this paper, the most recent applications of duplex treatment in tools were assembled, emphasizing the applications in HSS tools, whose number of published studies directed to practical applications is relatively small. The studies that contemplate the current discussions on the influence of thermal conductivity and superficial roughness in the performance of tools were also gathered. The following conclusions and perspectives were based on the published literature.

a) The duplex treatments proved to be indicated for application in forming tools and matrices, considerably increasing the wear resistance of steels applied in hot and cold forming dies. The positive results were associated to the following aspects: deposition of coating of high hardness and thermal stability, increase of compound hardness (coating plus substrate), hardness gradient established in plasma nitriding, lower difference between the rigidity of the substrate and of the coating in the region near the interface. Negative results were also found in the application of duplex treatment. These results were associated to the following aspects: deficient adhesion due to the formation of compounds layer during nitriding, inadequate temperature and times of treatment, inadequate support for forming with mechanical hammer due to the large oscillations of load and temperature, requiring the study of different parameters for nitriding. The duplex treatment also presented good results for hydro-abrasion resistance.Change number of columns: Select the Columns icon from the MS Word Standard toolbar and then select “1 Column” from the selection palette.

b) The application of duplex treatments in HSS tools improved significantly the tribological performance, as well as in the forming tools, which revealed that the improvements obtained with the application of treatment in other materials, which have a greater number of published studies, should be studied in HSS, due to the relative advantages of processing and cost. The positive results were once again associated to the unique support properties offered by the nitreted layer to a high hardness coating. The negatives showed that the depth of the nitreted layers should be controlled (limiting the time and temperature of the processing), especially at the edges of the tools, to avoid fracture of the cutting edges. The addition of an additional layer of perfluoropolyether solid lubricant (Z-DOL) on the deposited layer presented a positive impact on the reduction of wear.

c) The studies relating wear and thermal conductivity showed that coatings with low thermal conductivity contribute to reduce wear, decreasing the thermal load of the tool. It was observed that the performance of the coating in the decrease of the thermal load and consequently of the tool wear is directly linked to its anisotropy, revealing the tendency of higher efficiency for multilayer coatings with constituent layers presenting significant differences of thermal conductivity. The efficiency of the coatings against low machinability alloys was significantly positive.

d) It was demonstrated in all studied papers about the roughness-wear relation, that the increase of roughness contributes directly to the reduction in the wear resistance of the tools. The polishing treatment can contribute significantly to improve the performance of the tools, especially when applied after deposition.

e) Despite the positive effects demonstrated in the studies on application of duplex treatment in tools, the research in this area still has a lot to add. The small amount of published papers related to HSS reveal this deficiency, because with appropriate conditions of coating adhesion, the tribological behavior of the tool becomes determined by the coating properties and the HSS is a potential candidate as substrate for coatings applications through duplex treatment, due to its toughness, low cost and ease of processing.

f) The development of coatings with high degree of thermal anisotropy has few advances and can contribute significantly to the reduction of the costs of special components manufactured with titanium and nickel superalloys.

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