materials proceedings

MDPI

Proceeding Paper

Wear Behavior of Coated Tools When Milling S32101 Duplex Stainless Steel †

Francisco J. G. Silva [1,2,*], Vitor F. C. Sousa [1,2], Raúl D. S. G. Campilho [1,2] and Ricardo Alexandre [3]

1 ISEP—School of Engineering, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal; vcris@isep.ipp.pt (V.F.C.S.); raulcampilho@gmail.com (R.D.S.G.C.)
2 INEGI—Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal
3 TEandM—Tecnologia, Engenharia e Materiais, S.A., Zona Industrial do Taveiro, 41–42, 3045-504 Taveiro, Portugal; ricardo@teandm.pt
* Correspondence: fgs@isep.ipp.pt; Tel.: +351-228-340-500

† Presented at the Materiais 2022, Marinha Grande, Portugal, 10–13 April 2022.

Abstract: The growing demand for metals with high performance and optimal mechanical properties, especially in highly corrosive environments under high-temperature conditions, has led to the increased use of duplex stainless steels. Its applications are increasingly diverse, from the petrochemical industry to thermal and energy production facilities. Many of the components used in duplex stainless steel must undergo machining operations. However, this type of alloy is within the group of alloys considered difficult to machine. Effectively, in addition to the high mechanical strength characteristic of this alloy, the adhesion of this alloy to cutting tools is well known, leading to premature wear phenomena, which generates the excessive consumption of tools, with the consequent problems of economic and environmental sustainability. This study aims to evaluate the behavior improvement presented by tools coated with TiAlN and TiAlSiN when milling an alloy widely used in industrial terms: the UNS S32101 alloy.

Keywords: PVD-coated tools; machining; milling; wear behavior; duplex stainless steels; UNS S32101 alloy

Citation: Silva, F.J.G.; Sousa, V.F.C.; Campilho, R.D.S.G.; Alexandre, R. Wear Behavior of Coated Tools When Milling S32101 Duplex Stainless Steel. *Mater. Proc.* **2022**, *8*, 45. https://doi.org/10.3390/materproc2022008045

Academic Editors: Geoffrey Mitchell, Nuno Alves, Carla Moura and Joana Coutinho

Published: 27 May 2022

1. Introduction

When materials with extraordinary properties—in terms of both mechanical strength and corrosion resistance—are required, duplex stainless steels are always a promising option, as they combine high mechanical strength with exceptional corrosion resistance, even under high temperature conditions, as well as exhibiting high levels of toughness [1]. This is essentially due to an almost equitable distribution of phases in its microstructure, essentially consisting of ferrite and austenite [2]. The presented properties, clearly superior to most common austenitic stainless steels, have captured the attention of designers, increasing their range of applications, sometimes even to the detriment of nickel-based alloys due to their more attractive commercial cost than these Ni-based alloys, although they are still more costly when compared to most common stainless steels [3–5]. However, the difficulty that these alloys present in machining, due to their thermal conductivity, high tenacity, easy hardening when subjected to cold work, and strong tendency to form a built-up edge (BUE), is also well known [4]. The increase in friction caused by the cold work hardening effect is responsible for a significant increase in temperature on the surface of the cutting tool, which induces diffusion and oxidation phenomena [5]. In addition, the intense BUE formation and related adhesion phenomena between the duplex stainless steels and the cutting surface of the tool result in continuous chip formation and the further deterioration of the tool due to adhesive wear [6].

The machining of duplex stainless steels has been widely studied in diverse aspects, e.g., using different alloys within the same family of duplex stainless steels, as well as different types of tools, both in turning and milling operations. Given the difficulties mentioned above, the use of hard coatings performed in a vacuum, both by PVD (physical vapour deposition) and by CVD (chemical vapour deposition), has been a solution, showing promising results in most situations [7–9]. In the study of the milling process of duplex stainless steels, Selvaraj et al. [10] concluded that feed rate, spindle speed and axial depth increased the cutting force by about 46%, 27% and 21%, respectively. The parameters which conducted the lowest cutting force were 1000 rpm spindle rotation, 0.4 mm depth of cut, and 63 mm/min feed rate. The machined material was an ASTM A 995 5A cast duplex stainless steel alloy under dry machining conditions. Gouveia et al. [6] concluded that using four flutes produces a better surface finish on the workpiece in outside milling operations, but two flutes result in a better surface finish when slotting or down milling operations are performed, which is attributed to better chip extraction. In this study, TiAlN-coated tools provided with four flutes presented the best performance in external milling operations. Zhang et al. [11] determined that 1500 rpm spindle speed, 76.2 mm/min feed rate, and 1.52 mm depth of cut were the best conditions to reduce surface roughness in dry-milling duplex stainless steels, confirming that higher spindle speed, medium feed rate, and low depth of cut constitute the best set of conditions to be used in the aforementioned milling conditions. In fact, many studies have been carried out with a view to optimizing the parameters that lead to a better finish on the machined surface, but studies related to the analysis of the wear mechanisms that affect coated tools are scarcer, and each one has been carried out according to a specific set of machining conditions, which prevents a generalization of the observed phenomena.

2. Experimental

Coating thickness, composition and tool wear scars were investigated using an FEI Quanta 400FEG scanning electron microscope equipped with an Energy Dispersive X-ray Spectroscope (EDS) EDAX Genesis. The tools' performance was evaluated through milling tests carried out in a 20 kW HAAS VF2 CNC milling center using an externally projected cutting emulsion (5% oil in water). The radial and vertical depth of cut were kept constant for all milling tests, at 3 mm and 0.08 mm, respectively, at a cutting speed of 60 m/min. The selected value for the feed rate was 480 mm/min, which was compared with another two values: 600 mm/min (+25%) and 360 mm/min (−25%). Two different cutting lengths were selected: 2 m and 4 m. These values were chosen regarding the preliminary test results, which allowed us to conclude that cutting forces increased after 2 m of cutting length. Four flutes and four-millimeter-diameter tungsten carbide tools coated with TiAlN and TiAlSiN by PVD were used, the thickness of these coatings being 2.81 ± 0.12 µm and 2.80 ± 0.16 µm, respectively. Coating hardness and corresponding Young's modulus were assessed using a Fischerscope H100 dynamic ultra-micro hardness tester. The flank wear (VB) was analyzed by SEM + EDS following the ISO 8688-2:1986 standard, and the workpiece surface roughness was evaluated using a Mahr Perthometer M2 profilometer. Three tests under each set of cutting conditions were performed to increase the reliability of the results.

3. Results and Discussion

The first evaluation carried out corresponded to the thickness of the coatings deposited on the tools to confirm whether the obtained thickness was in accordance with the desired values, verifying that they were relatively close to the 3 µm initially specified. Then, the hardness tests were performed on a sample coated in the same tool deposition batch, having been submitted to the same deposition conditions. The values obtained for the hardness of the TiAlN and TiAlSiN coatings were very similar, i.e., 22.9 ± 1.2 GPa and 21.6 ± 0.9 GPa, respectively. Regarding the Young's Modulus, the values recorded were 312 ± 9 GPa for TiAlN, and 266 ± 7 GPa for TiAlSiN. On the other hand, the Hardness/Young's Modulus ratio, H/E, which is also important to consider for wear evaluation, was 0.073 and 0.081 for the TiAlN and TiAlSiN coatings, respectively.

The profilometric analysis of the machined surface showed that an increase in the feed rate also promoted an increase in the arithmetic mean roughness (Ra) left on the surface by the TiAlN-coated tool, which evolved from 0.29 ± 0.02 μm (f = 360 mm/min, 2 m cutting length) to 0.51 ± 0.04 μm (f = 600 mm/min, 4 m cutting length). Regarding the TiAlSiN-coated tools, there was also an increase in the surface roughness value with the increase in the feed rate, but on a smaller scale: from 0.194 ± 0.018 μm (f = 360 mm/min, 2 m cutting length) to a maximum value of 0.284 ± 0.033 μm (f = 600 mm/min, 4 m cutting length). As can be seen, the maximum value of Ra obtained with the TiAlSiN-coated tools was about half of the value obtained with the TiAlN-coated tools, revealing that the surface finish left by the TiAlSiN-coated tool, for the same cutting conditions, was of higher quality (even for the same cutting length). This behavior is in line with other observations previously reported in other works [1,6,12]. The values of the machined surface roughness are normally correlated with the wear seen on the tools, so it was necessary to analyze the cutting edges of the different tools.

Regarding the tool flank wear (VB) values, they ranged from 7040 ± 0.24 μm for f = 480 mm/min and 2 m cutting length to 25.12 ± 1.05 μm for f = 600 mm/min and 4 m cutting length for the TiAlN-coated tools, and from 4770 ± 0.22 μm for f = 600 mm/min and 2 m cutting length to 18.80 ± 1.16 μm for f = 480 mm/min and 4 m cutting length for the provided tools with the PVD TiAlSiN coating. Thus, it was possible to verify that the TiAlN coating provided an evolution of wear that worsened whenever the feed rate or cutting distance was increased, a situation that was not observed in the case of the TiAlSiN-coated tools. In fact, the TiAlSiN coating exhibited a greater resistance to feed rate increment, showing even the best result for the highest tested feed rate (600 mm/min) and the 2 m cutting length. However, for the same parameters, but doubling the cut distance to 4 m, there was a very small increase in VB, from 4770 ± 0.22 μm to 5830 ± 0.65 μm. These values clearly demonstrate that the wear behavior of the coatings was significantly different, since the introduction of Si in the coating composition gave better wear resistance properties when in lubricated cutting conditions during milling.

The origin and evolution of wear was also analyzed through SEM observations. This analysis showed that there was no clear effect of BUE, but there was an abundant adhesion of duplex stainless steel to the coated tool's surface. This adhesion evolves over time during the cutting process and, due to the cutting action of the material that is being removed from the workpiece and passing tangentially to its surface, it tends to tear off parts of the coating in the most stressed areas. This phenomenon of coating delamination, together with the phenomenon of abrasion that also acts permanently on the tool's surface, leads to a reduction in the coating's thickness in certain areas, and even being torn off in certain areas. Figure 1 (on the left), corresponding to one of the TiAlN-coated tools, clearly shows a failure of the coating after the previous adhesion of the material to the tool's surface, which later evolved to coating delamination. In another area of the same surface of the tool (Figure 1, on the right), it is possible to observe that the coating is partially removed from the substrate, which exhibits a clear color. Moreover, it is also possible to observe some remnants of the abraded coating in a medium hue, clearly showing that only a very thin part of the coating remained adhered to the substrate. Furthermore, the grooves left by the grinding process used to produce the tool surface were used by the wear mechanisms to promote the evolution of the cracks, helping with the coating degradation and the corresponding peeling. Thus, the coating degradation was gradual and these grooves were used to progress it.

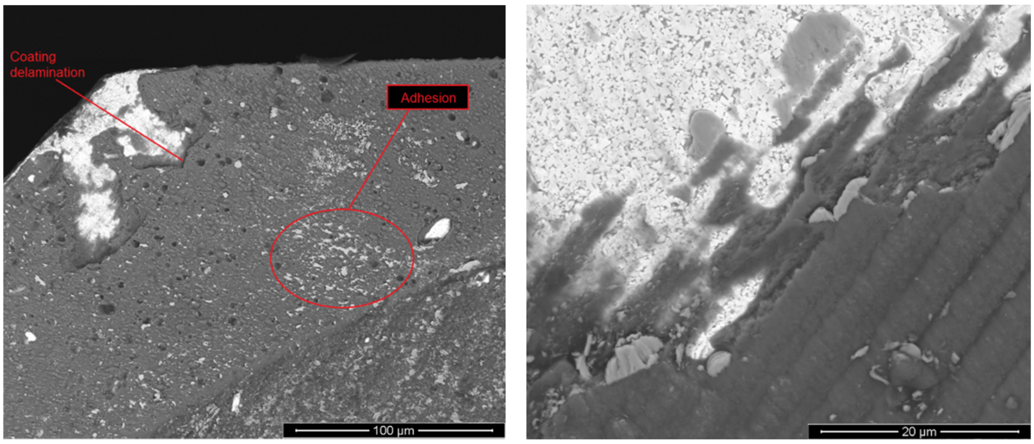

Figure 1. TiAlN-coated tool after 2 m cutting length and 480 mm/min feed rate (on the left) and TiAlSiN-coated tool after 4 m cutting length and 480 mm/min feed rate (on the left).

4. Conclusions

After carrying out the machining tests, it is possible to state that the TiAlSiN coatings deposited on the cemented carbide tools presented better wear performance than the TiAlN-coated tools under the same lubricated milling conditions, giving rise to a better surface finish as well. TiAlSiN coatings can accommodate higher feed rate values and higher cutting distances, showing less coating wear and a better surface quality of the workpiece.

Author Contributions: Conceptualization, F.J.G.S., V.F.C.S. and R.D.S.G.C.; methodology, F.J.G.S.; validation, R.D.S.G.C. and R.A.; formal analysis, R.D.S.G.C. and R.A.; investigation, V.F.C.S.; resources, F.J.G.S. and R.A.; data curation, R.A.; writing—original draft preparation, F.J.G.S.; writing—review and editing, V.F.C.S.; visualization, R.D.S.G.C.; supervision, F.J.G.S.; project administration, F.J.G.S. and R.A. All authors have read and agreed to the published version of the manuscript.

Funding: The present work was conducted and funded under the scope of the project ON-SURF (ANI | P2020 | POCI-01-0247-FEDER-024521, co-funded by Portugal 2020 and FEDER, through the COMPETE 2020-Operational Programme for Competitiveness and Internationalisation.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: F.J.G. Silva thanks INEGI—Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Indústria for its support. The authors would like to thank Rui Rocha from CEMUP (Porto, Portugal), due to his active collaboration in getting the best SEM pictures and helping with his critical analysis of some phenomena. The authors also would like to thank Ing. Ricardo Alexandre for his extremely important role in providing all the coatings through the TEandM company, and Eng. Nuno André for providing the substrate material and uncoated tools through the Inovatools company.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Silva, F.J.G.; Martinho, R.P.; Martins, C.; Lopes, H.; Gouveia, R.M. Machining GX2CrNiMoN26-7-4 DSS Alloy: Wear Analysis of TiAlN and TiCN/Al_2O_3/TiN Coated Carbide Tools Behavior in Rough End Milling Operations. *Coating* **2019**, *9*, 392. [CrossRef]
2. Cheng, X.; Wang, Y.; Li, X.; Dong, C. Interaction between austein-ferrite phases on passive performance of 2205 duplex stainless steel. *J. Mater. Sci. Technol.* **2018**, *34*, 2140–2148. [CrossRef]
3. Zhang, Z.; Zhang, H.; Hu, J.; Qi, X.; Bian, Y.; Shen, A.; Xu, P.; Zhao, Y. Microstructure evolution and mechanical properties of briefly heat-treated SAF 2507 super duplex stainless steel welds. *Constr. Build. Mater.* **2018**, *168*, 338–345. [CrossRef]
4. Jebaraj, A.V.; Ajaykumar, L.; Deepak, C.R.; Aditya, K.V.V. Weldability, machinability and surfacing of commercial duplex stainless steel AISI2205 for marine applications—A recent review. *J. Adv. Res.* **2017**, *8*, 183–199. [CrossRef] [PubMed]

5. Martinho, R.P.; Silva, F.J.G.; Martins, C.; Lopes, H. Comparative study of PVD and CVD cutting tools performance in milling of duplex stainless steel. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 2423–2439. [CrossRef]
6. Gouveia, R.M.; Silva, F.J.G.; Reis, P.; Baptista, A.P.M. Machining Duplex Stainless Steel: Comparative Study Regarding End Mill Coated Tools. *Coatings* **2016**, *6*, 51. [CrossRef]
7. Sousa, V.F.C.; Silva, F.J.G. Recent Advances on Coated Milling Tool Technology—A Comprehensive Review. *Coatings* **2020**, *10*, 235. [CrossRef]
8. Sousa, V.F.C.; Silva, F.J.G. Recent Advances in Turning Processes Using Coated Tools—A Comprehensive Review. *Metals* **2020**, *10*, 170. [CrossRef]
9. Martinho, R.P.; Silva, F.J.G.; Baptista, A.P.M. Cutting forces and wear analysis of Si_3N_4 diamond coated tools in high-speed machining. *Vacuum* **2008**, *82*, 1415–1420. [CrossRef]
10. Selvaraj, D.P. Optimization of cutting force of duplex stainless steel in dry milling operation. *Mater. Today Proc.* **2017**, *4*, 11141–11147. [CrossRef]
11. Zhang, J.Z.; Chen, J.C.; Kirby, E.D. Surface roughness optimization in an end-milling operation using the Taguchi designmethod. *J. Mater. Process. Technol.* **2007**, *184*, 233–239. [CrossRef]
12. Airao, J.; Chaudhary, B.; Bajpai, V.; Khanna, N. An Experimental Study of Surface Roughness Variation in End Milling of Super Duplex 2507 Stainless Steel. *Mater. Today Proc.* **2018**, *5*, 3682–3689. [CrossRef]