COBEM 2023
27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM
Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0558
INFLUENCE OF TOOL WEAR ON THE SURFACE ROUGHNESS OF SPLINED SHAFTS GENERATED BY HOBBING PROCESS

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Abstract. *The hob is the most used machining process in gear manufacturing, generating all gear surfaces in a single process. The surface roughness of the involute profile of the gear tooth is highly relevant for engineering, as it directly influences the coefficient of friction generated in the sliding of the involute surfaces during gearing, generating more heat, higher noise levels, speed oscillations, loss of precision and efficiency of the transmission system. Besides, it directly impacts the life of gears by increasing tooth wear. Thus, the present work evaluates the influence of maximum flank wear (VBmax) of hobs coated with three different PVD coatings (TiN, TiAlN, and CrAlN) on the surface roughness of splined shafts manufactured in SAE 8620 hardened steel, seeking a correlation of Ra and Rz roughness values with each type of coating used. It was noted that there is a tendency for increasing roughness values as tool wear increases until it reaches a critical point (VBmax ≅ 0.1 mm). There is a tendency for decreasing roughness values, probably due to an increased tool tip radius. It was also observed that the TiN-coated tool showed the highest values of hob wear and splined shaft tooth roughness, the TiAlN-coated tool showed the lowest Ra and Rz values of hob wear, and the CrAlN-coated tool, even with intermediate wear, showed the lowest roughness values of the splined shaft tooth. The CrAlN-coating also showed less variation of roughness values throughout the entire process and minor mean deviations. The textures of the splined shafts were also evaluated, where the abrasive marks were found. These marks were more present when the hob with a less hardened coating was used (VBmax ≤ 0.07 mm). Furthermore, attrition marks were equally distributed in the cutting direction of the tool, where the CrAlN-coated tool produced these marks in smaller amounts and dimensions.*

Keywords: *Hobbing, Wear, Tool coating.*

1. INTRODUCTION

Gears have been the most used machine element by humanity in different applications for more than 2,000 years. They currently have a wide range of applications, such as mobility (transmission boxes), power generation (wind generator), agriculture, etc. (Karpuschewski et al., 2020). Surface quality is necessary for heavy and precision transmission applications (Nguyen et al., 2020) since gears determine equipment performance, durability, safety, and reliability (Sun et al., 2018).

Hobbing is a machining process widely used in the industry only to manufacture cylindrical gears with straight and helical teeth. This process has a simple tooling configuration, with a hob tool that cuts the material, resulting in high efficiency and good reliability. However, tool wear reduces this efficiency and the surface quality of the produced gears (Chang et al., 1997). In this case, the hob can present different types of wear, whose the most common is flank wear (Fig. 1), which occurs mainly by abrasion due to the contact between the workpiece and tool. This wear impairs the part finishing and can cause dimensional changes (Diniz et al., 2013). On the other hand, crater wear and chipping practically do not exist in coated tools (Lima, 1995).

Surface roughness is an important characteristic, as it directly affects the contact between teeth, i.e., teeth with lower roughness values have a larger contact area (Bergseth et al., 2012; Seabra, 2003). However, tool wear directly influences the machined surface quality. Diniz and Calderai (2002) observed in the end milling with carbide tool a slight increase in average roughness (Ra) as the tools show extensive wear, with a more significant growth when the cutter is close to its end of life (VB = 0.7 mm). Moreover, higher roughness values generated in the end milling with high cutting speeds occurred due to increased tool wear rate.

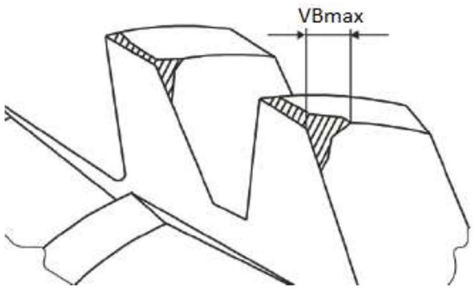
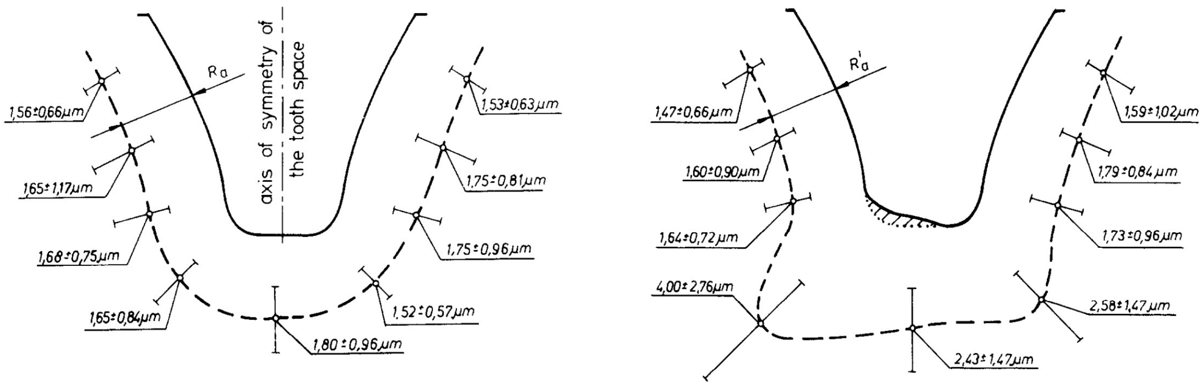


Figure 1. Maximum flank wear on the tool hob (Stachurski, 2012)

The increase in roughness values leads to a rise in the friction coefficient and the gear wear rate, the latter being affected more significantly and non-linearly (Masjedi and Khonsari, 2015). Besides, roughness values increase with increasing machining time for solid carbide end mills and indexable inserts (Dadgari et al., 2018; Hamano, 2017). In addition, hob flank wear affects, even if slightly, the surface roughness of the machined tooth, having a more relevant impact on microhardness and residual stresses (Korzeniewski and Kruszyfuski, 1983). Fig. 2 shows the tendency for roughness values to be higher after hobbing with worn hobs.



(a) (b)

Figure 2. Surface roughness distributed along the gear tooth space profile obtained with: (a) a sharp tool; (b) a worn tool with VB_{max} = 4,6 mm (Korzeniewski and Kruszyfuski, 1983)

Nevertheless, different authors (Bergs et al., 2019; Gerth et al., 2009; Rheinheimer, 2018) observed that the extensive flank wear (Fig. 3) promoted lower roughness values, as this wear increased the tool tip radius. However, this radius growth generated more extensive geometric deviations and raised the temperature in the cutting region. As this radius increases, the roughness values tend to decrease to a certain extent; from that point on, the effects of increasing the tool tip radius, such as the increase in vibrations and the required machining force, cause an expressive deterioration in the generated surface quality (Amorim, 2002).

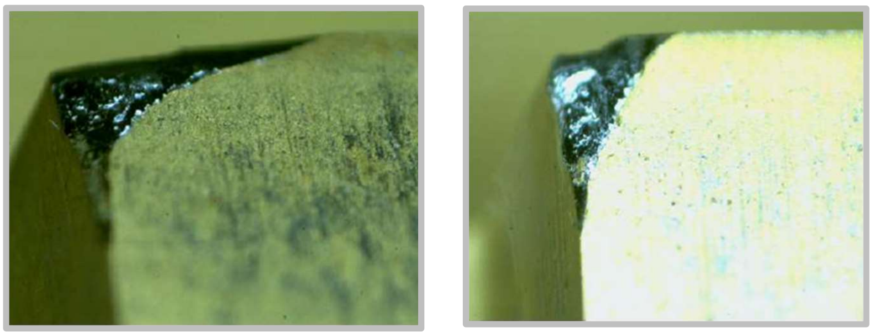


Figure 3. Examples of flank wear on the hob tip (Rheinheimer, 2018)

Moura (2012) mentions that coated tools tend to promote good workpiece surface roughness stability throughout the machining. According to Rheinheimer (2018), coatings with greater hardness provide a lower tool wear rate due to higher protection against the abrasion mechanism and, therefore, longer hob life. However, higher hardness (and consequently lower tenacity) tends to weaken the coating and cause microchipping, which affects the workpiece surface quality.

Rheinheimer (2018) analyzed the texture of splined steel shafts hardened to 32~34 HRC, manufactured by hobbing, applying carbide tools with different PVD coatings (TiN, TiAlN, and CrAlN). The author observed abrasion marks between the workpiece and hob and adhesion marks equally distanced along the workpiece toward the tool feed. These marks were more predominant in conditions without tool wear and less recurrent in workpieces machined with TiN-coated tools. The most likely explanation for this phenomenon is the different thermal conductivities in the coatings, which lead to diverse degrees of material adhesion.

Thus, the present work aims to evaluate the influence of hob wear with three different types of PVD coatings (TiN, TiAlN, and CrAlN) on the surface roughness obtained in a splined shaft generated through the hobbing process, seeking a correlation of the values presented for each type of coating.

2. MATERIALS AND METHODS

The experiment involved the generation of teeth on SAE 8620 splined shafts (Fig. 4), quenched and tempered with a hardness of 33 ± 1 HRC, by the hobbing process using a generating machine Athena module 8 gear with a 500 mm diameter table and a feed stroke of 300 mm (Fig. 5).

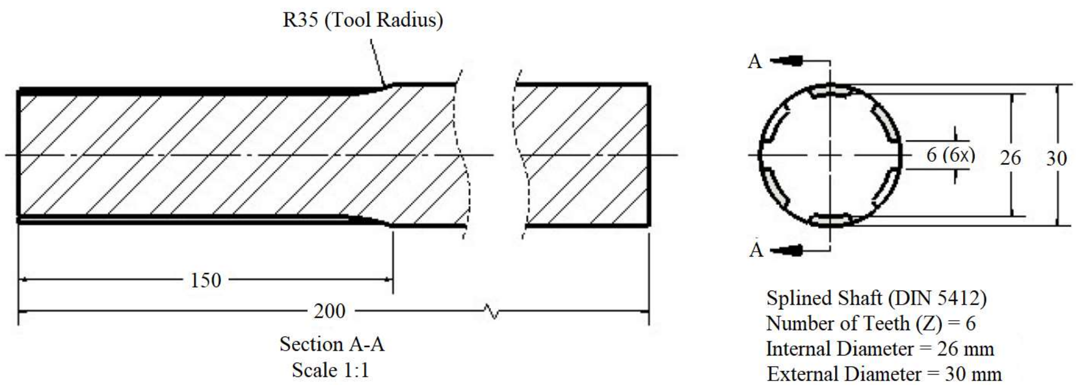


Figure 4. Workpiece manufactured by hobbing (Rheinheimer, 2018)

Figure 5. Gear manufacturing machine (Rheinheimer, 2018)

Carbide hobs were used because most applications used this tooling material. The tool manufacturer is FABHERCO (FB), and the geometry of the cutting edges is established according to the DIN 5412 standard. The hob has 14 teeth rows, each with four or five teeth, and each tooth has a main cutting edge and two side cutting edges. Tools with three coatings (TiN, TiAlN, and CrAlN) were applied to the hob, as illustrated in Fig. 6.

(a) (b) (c)

Figure 6. Hobs with coatings: (a) TiN; (b) TiAlN; (c) CrAlN.

Five parts were machined with each coated tool, producing a machining volume of 15,450 mm^3 per workpiece. Therefore, the volume of 77,250 mm^3 was the final test criterion. Considering one repetition, 30 machined samples were generated by climb milling that was applied to achieve high tool wear during the machining of the samples. The cutting parameters were kept constant: cutting speed v_c = 65 m/min, depth of cut a_p = 2.0 mm (total tooth height), and feed rate v_f = 0.8 mm/min. A Cutlube 25® mineral-based integral oil was applied at a flow rate of approximately 10 l/h.

Hob wear was measured using an Optiv Lite OLM 3020 profile projector using a magnification of 81.6x. A guideline on the tool cutting edge and another parallel, concurrent with the observed maximum flank wear point (VBmax), were created. Figure 7 shows the VBmax measurement procedure. Wear was checked on all cutting edges, but only the one with the highest VBmax has been registered.

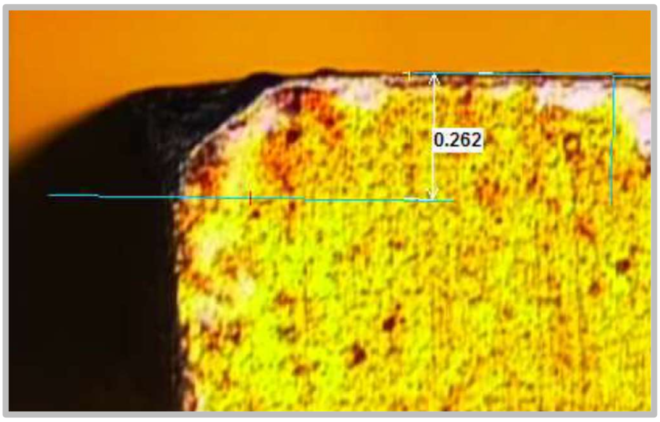
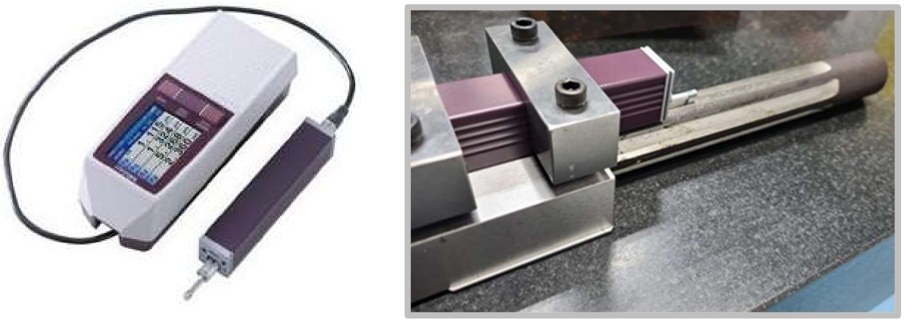


Figure 7. Wear measuring method (Rheinheimer, 2018)

In this work, the *Ra* and *Rz* values of all samples were measured using the Mitutoyo SJ-210 portable roughness meter (Fig. 8a). Measurements were taken in the middle of the workpiece and the tool feed direction (Fig. 8b). The arithmetic mean of three collected values in each workpiece, in different grooves, was considered. A sampling length l_e = 0.8 mm and a measuring length l_m = 6 x 0.8 = 4.8 mm were used.



(a) (b)

Figure 8. (a) Rugosimeter SJ-210; (b) Surface roughness measurement

Due to its ease of obtaining, the average roughness parameter (*Ra*) is applied in production lines when it is necessary to carry out continuous surface roughness control and in machined parts where the surface has well-defined feed marks (periodic profile). The main disadvantage is that Ra represents the arithmetic mean of the absolute height values along the measuring length (l_m); thus, if a non-typical peak or valley appears on the surface, the average value will not change much, hiding the defect. *Rz* is the average of the maximum peak-to-valley height values at consecutive sampling lengths (l_e) within the l_m. Thus, *Rz* is the parameter used to complement *Ra* because it better identifies the presence of peaks or valleys on surfaces where the roughness profile is periodic and well-defined (Agostinho, 2020).

Finally, a statistical treatment was applied to the values found, i.e., the arithmetic mean and standard error were calculated in each of the five workpieces, relating the roughness to the existing wear on the coated carbide tool.

3. RESULTS AND DISCUSSIONS

Figure 9 shows the graph of maximum flank wear (VBmax) as a function of the number of manufactured parts. It observes that the TiAlN-coated hob showed the lowest tool wear values statistically equal to the CrAlN-coated hob. These coatings have increased abrasion resistance in common due to the high hardness obtained by applying them. It is also noted that the adhesion mechanism becomes predominant when using any of these coatings (Moura, 2012). In this work, as the sample used was made of a fragile material (due to heat treatment), it was not expected to find adhesive wear.

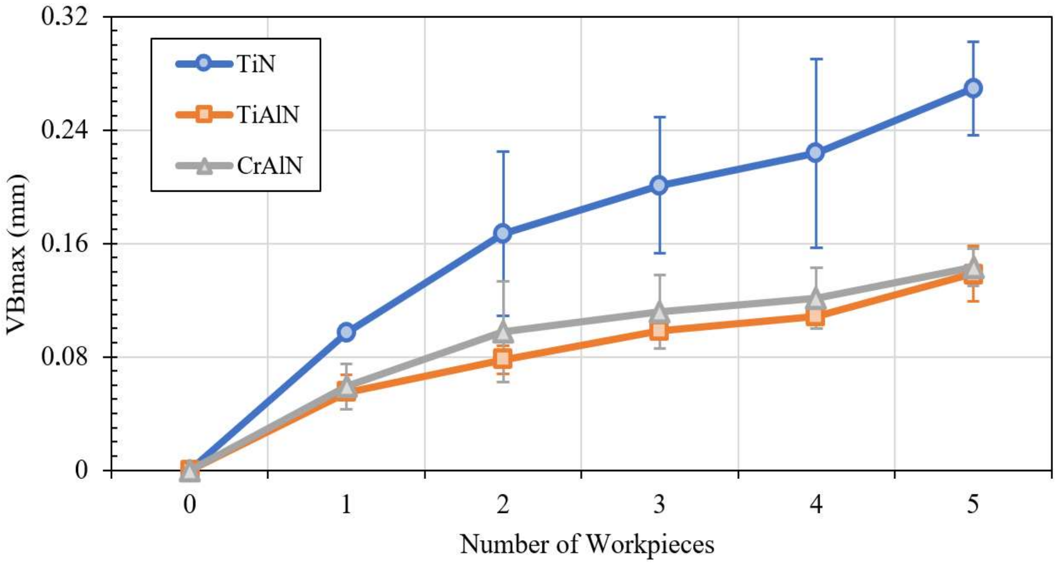


Figure 9. Maximum flank wear *versus* number of machined workpieces

The TiN-coated carbide hob showed the highest VBmax values (Fig. 9) and, therefore, the highest roughness values (Ra = 1.23 ± 0.87 µm and Rz = 7.30 ± 5.26 µm), as shown in Fig. 10. Similarly, Santos (2004) concluded that high-speed steel hobs with TiAlN coating had a longer tool life and produced gears with lower roughness values when compared to those with TiN coating. In the case of the present study, the TiAlN-coated carbide hob generated Ra = 0.99 ± 0.75 µm and Rz = 6.21 ± 4.27 µm. In addition, Sortino (2015) found that carbide tools with CrAlN coating had longer tool life compared to other coatings when milling nickel-based alloys; in addition, the author noted that the TiAlN-coated tool had a lower life than with CrAlN coating.

The CrAlN was the coating that generated the lowest roughness values and showed excellent stability throughout the entire process, with more constant values regardless of tool wear (Ra = 0.50 ± 0.10 µm and Rz = 2.52 ± 0.43 µm). This less variation of roughness values could also be verified in the machined workpiece itself, being the coating that presented the lowest maximum errors. This performance can be explained by the fact that the CrAlN-coated tool had low wear values, which did not change the geometry of the tool's cutting wedge during machining, in addition to CrAlN has a lower friction coefficient under light and severe sliding conditions (Aihua et al., 2012) that are considered foremost in hobbing.

According to Agostinho (2020), the higher the result of the *Ra* / *Rz* ratio, the better the roughness profile, with peaks and valleys of great amplitude in smaller amounts. In this sense, Fig. 10 shows the best condition was obtained when using CrAlN coating (0.202 ± 0.055). In addition, it can be seen that there is a tendency to improve the roughness profile due to extensive tool tip wear, similar to the turning process. Finally, the coating that produced the lowest *Ra* / *Rz* ratio was the TiAlN (0.161 ± 0.039), followed by TiN (0.178 ± 0.043).

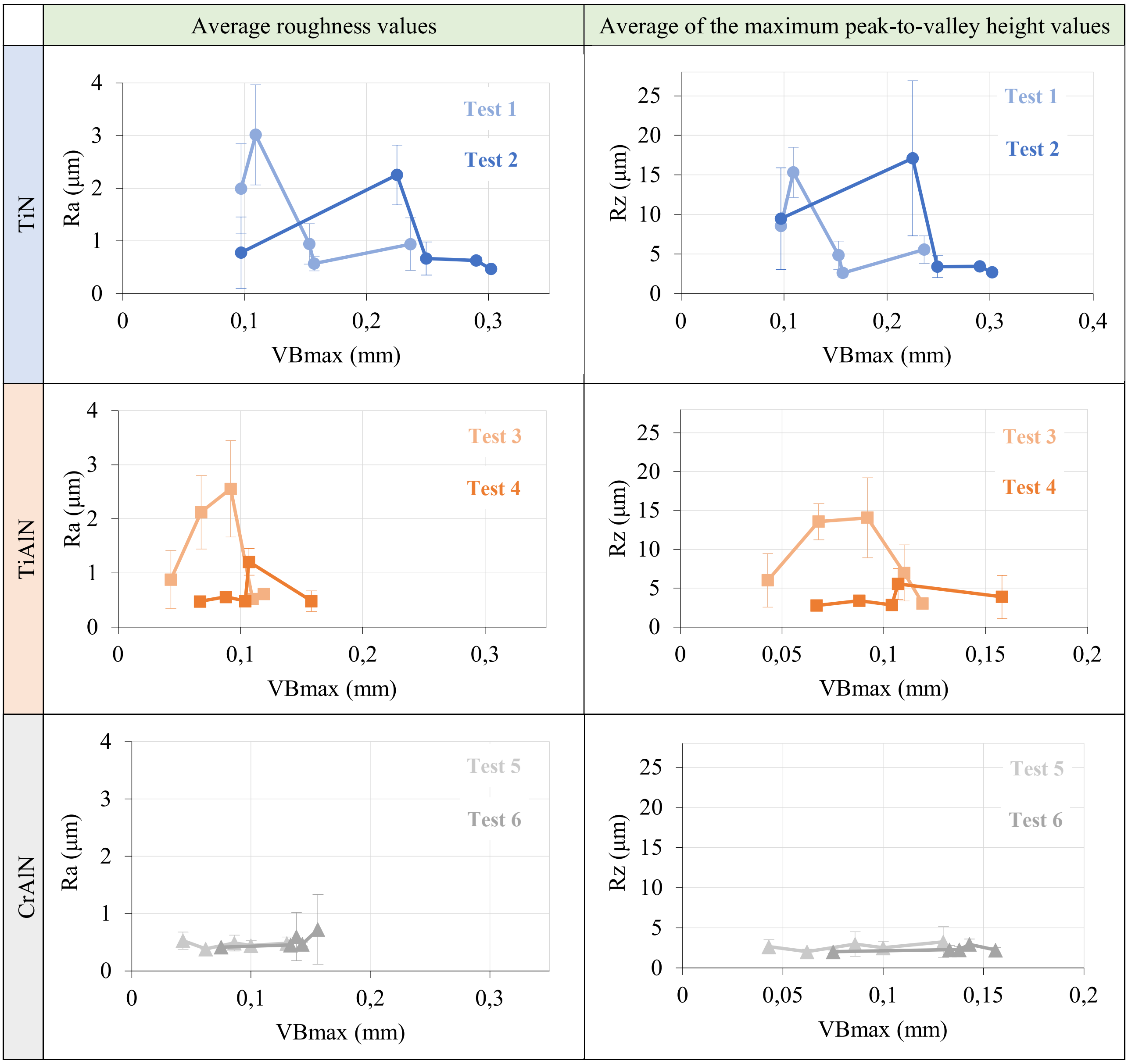


Figure 10. *Ra* and Rz surface roughness values versus maximum flank wear

Figure 11 shows the images of workpiece-surface textures machined with the three coated carbide hobs of the study. A tendency to increase the roughness values with the rise of VBmax is observed for all the coatings used until the maximum flank wear reaches a critical point (approximately 0.1 mm). From that level, there is a tendency for roughness values to decrease. Similar results were found by Bergs et al. (2019). According to Amorim (2002), this can be explained by the increase in the tool tip radius caused by flank wear.

Abrasion marks were found on the part, larger in conditions where the tool generally had no flank wear. Attrition marks were also found equally spaced in the direction of the tool feed, along the workpiece, being more predominant in cases without tool wear (and less recurrent in samples machined with TiN-coated tool); the most likely explanation for this phenomenon is the different thermal conductivities of the coatings (Rheinheimer, 2018). It was initially speculated that the abrasion marks on the surfaces generated with TiN- and CrAlN-coated tools would present this characteristic, given that these two coatings have a higher hardness, close to 2600 HV, compared to TiAlN with a hardness of approximately 1500 HV (Vettivel at al., 2017). However, they were more detectable on surfaces generated with a hob coated with CrAlN. In addition, because the CrAlN coating has better thermal stability, even at high temperatures (Vettivel et al., 2017), the surfaces generated by this tool showed lower attrition marks in smaller quantities.

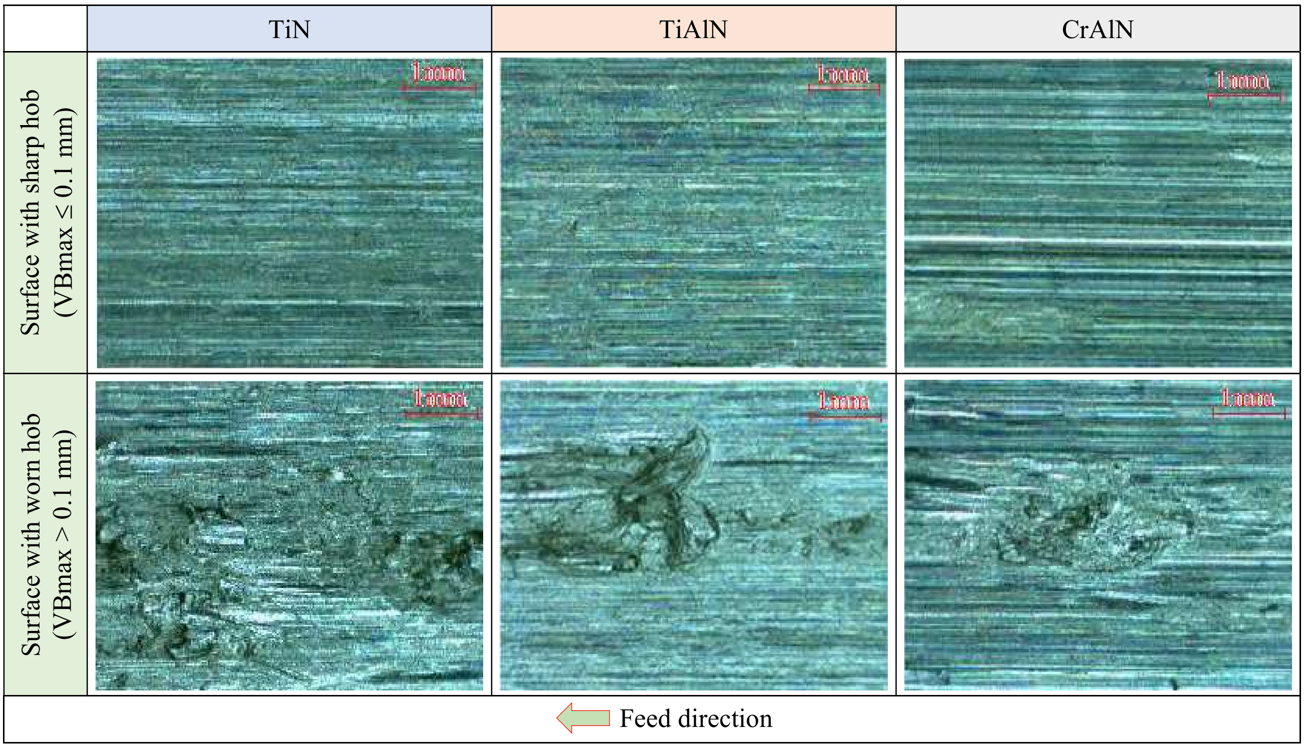


Figure 11. Surface textures produced by new and worn TiN-, TiAlN- and CrAlN-coated hobs.

4. CONCLUSIONS

The present paper contributed to a better understanding of the relationship between the coating type, tool wear, and surface roughness obtained by the hobbing process.

The evaluation of the surface roughness obtained with the different levels of hob wear showed that initially, there is an increase in roughness values as the tool wear also increases until reaching a certain point. After that, possibly due to the rise of the tool tip radius by abrasive wear, the roughness values decreased. When the tool wear exceeds a certain point, other adverse effects arising from this increase in wear start to negatively influence the machined surface.

The TiN-coated tool generated the worst results for roughness values, while the CrAlN-coated tool produced the best. Furthermore, CrAlN behaved with less variation of surface roughness throughout the process.

5. ACKNOWLEDGEMENTS

I thank the company WM TOOLS for the support provided.

This work has been partially funded by the Brazilian agency CAPES

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