Performance of ISO P and ISO S carbide tools in hard turning of AISI 4140 under dry and MQL conditions

Rendimiento de las herramientas de metal duro ISO P e ISO S en el torneado de AISI 4140 endurecido en condiciones seco y con MQL

Matheus S. Polly[1] Amália Mayrhofer[1] André J. Souza[1]*

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ABSTRACT

The literature review shows few studies concerning the turning of hardened steels using carbide tools. A research in this case can provide a better understanding and an option of inserts with less cost than usually applied ceramic and CBN (cubic boron nitride) inserts. Thus, the objective is to investigate the tool-life of ISO P and ISO S grade coated carbide inserts and average roughness (R_a) of the machined surface generated with these tools in the hard turning of AISI 4140 steel under dry and minimum-quantity of lubrication (MQL) conditions. Comparing the ISO P and ISO S grades tool life in two different cutting speed levels (60 and 120 m/min), the higher cutting speed generated the lowest R_a values. Relating the lubri-cooling conditions, dry turning resulted in lower R_a values. When the tool nose wear does not change during the passes, the R_a remains constant. In addition, ISO S grade coated carbide insert has shown a possibility for this hard turning due to the low tool nose wear at a relatively high cutting speed.

Keywords: Hardened AISI 4140 steel, coated carbide tools, surface roughness, tool nose wear.

RESUMEN

La revisión de la literatura muestra que existen pocos estudios sobre el torneado de los aceros endurecidos utilizando herramientas de metal duro. Una investigación en este caso puede proporcionar una mejor comprensión y la opción de reducir costo es usando los insertos de cerámica y CBN (nitruro de boro cúbico). Por tanto, el objetivo es investigar la vida útil de insertos de metal duro con recubrimiento calidades ISO P e ISO S y la rugosidad media (R_a) de la superficie mecanizada con estas herramientas en el torneado duro del acero AISI 4140 en las condiciones en seco y con una cantidad mínima de lubricante (MQL). En la comparación de la vida de las herramientas ISO P e ISO S en dos niveles de velocidades de corte (60 y 120 m/min), para la mayor velocidad de corte se generaron los valores más bajos de R_a. Al relacionar las condiciones de lubri-refrigeración, los valores más bajos de R_a resultaron con el torneado en seco. Cuando el desgaste de la punta de la herramienta no cambia durante los pases, el valor de R_a permanece constante. Además, el inserto de metal duro con recubrimiento calidad ISO S ha mostrado la posibilidad de usar en el torneado duro debido al bajo desgaste de la punta de la herramienta en una velocidad de corte relativamente alta.

Palabras clave: Acero AISI 4140 endurecido, herramientas de metal duro con recubrimiento, rugosidad superficial, desgaste de la punta de la herramienta.

[1] Universidade Federal do Rio Grande do Sul (UFRGS). Department of Mechanical Engineering (DEMEC). Porto Alegre, Brazil. E-mail: matheuspolly32@gmail.com; amalia_19_@hotmail.com; ajsouza@ufrgs.br
* Corresponding Author: ajsouza@ufrgs.br

INTRODUCTION

Traditionally, the finish operations in machine components with hardness up to 60 HRC are made by grinding process. Recently, the machining of hard materials with geometrically defined cutting edges is increasingly able to replace the grinding and ensure a surface finish similar to this process [1]. Although the effectiveness of hard turning in terms of cost, cutting time, environment and competitiveness with grinding process, its industrial application is still limited due to uncertainties related to surface integrity, part precision, tool failure, estimation of tool-life and economic viability. Definitely, a research is necessary for hard turning to become more competitive and more economically effective than grinding [2-3]. In particular, hard turning applying ceramic or cubic-boron nitride (CBN) tools can generally reduce manufacturing costs, decrease lead-time, improve overall product quality, provide greater flexibility and allow dry machining (eliminating cutting fluids) [4-6]. The literature reports many studies using CBN tools in hardened steel turning, but it is also important to know the results when using coated carbide tools, mainly for economic reasons [7-10].

The characteristic most frequently investigated in machining hard materials, mainly due to the continuous competition between hard turning and grinding processes, is the surface roughness [2-3]. The surface roughness is composed of fine irregularities or micro-geometric errors resulting from the inherent action of the cutting process (feed-rate marks, built-up layer, tool wear, etc.). In many cases, surface roughness parameters are used as an output variable to control a machining process. In fact, the surface roughness depends on a several factors, such as machine tool, workpiece material properties, tool geometry and material, and cutting operation [11]. In addition to the factors that traditionally affect the surface roughness (i.e. feed-rate and tool nose radius), a special attention should be given to the deterioration of the tool nose edge in hard turning. In this case, faster tool-wear rates are observed, especially when the tool grade is not correctly selected, then resulting in poor surface finish [12].

Flank wear is generally larger than crater wear in coated carbide tools. The tool wear gradually increases until the cutting-edge breakage, which need to be avoided due to its harmful consequences. In finishing turning, the cutting edge must be replaced before the tool wear reaches values that threaten it in order to not affect the dimensional and surface quality of the workpiece [11-13]. A method to reduce the tool-wear rate is by adopting cutting fluids.

Machining process uses cutting fluids to reduce friction on chip-tool and tool-workpiece interfaces, to cool the cutting zone, and to remove the chips from the cutting region. Additionally, this provides to reduce tool-wear rate, minimize machining force, improve surface integrity of the workpiece, and protect the machined surface against corrosion. However, considering environmental aspects, the cutting fluids are complex mixtures that contain distinct components, some of which are toxic. Constant exposure to these fluids poses serious risks to the operator's health. Furthermore, the disposal of cutting fluids increases the cost due to the chemical treatment required. In recent years, a great effort to eradicate these adverse effects was carried out with an important focus on the minimum-quantity of lubrication (MQL) [14-15]. Besides, in machining at high cutting speed, the MQL is more efficient than flood cutting fluid, as it more easily penetrates the chip-tool and tool-workpiece interfaces [16-17].

Studies point to the effectiveness of the application of MQL in steel turning. In [18], the machining performance of AISI 4340 steel under MQL turning is better than dry turning because both the machining force components and cutting tool temperature decrease, which consequently favors chip-tool interaction and maintains the cutting edges sharp. In [19], the application of MQL overcomes the lubri-cooling strategies on dry, compressed air cooling and flood cutting fluid due to the lower surface roughness and reduced tool-wear rate generated by AISI 4340 turning. This is due to the reduction of cutting temperature and the best chip flow. The work [20] compared the AISI 4140 turning under dry, MQL, and flood conditions in terms of machining forces, surface roughness and temperature distribution and concluded that MQL turning is better than dry and flood turning. The MQL provides the benefits, mainly through reduction of cutting force components, favorable chip-tool interaction and cutting temperature low. In addition, the machined surface finish has improved, mainly due to decrease of the tool-wear rate and to reduction of chipping occurrence near the tool nose edge by MQL application.

Therefore, it is intended to comparatively evaluate the nose wear of carbide inserts ISO P grade and ISO S grade coated carbide inserts, and the average surface roughness (R_a) generated by these tools during the hard turning of AISI 4140 steel under dry and MQL conditions.

MATERIALS AND METHODS

Eight hardened AISI 4140 cylindrical bars at (53 ± 2) HRC with 75 mm diameter and 93 mm length are used in this work. Table 1 shows the main chemical elements of work material.

Two Sandvik coated carbide tools for finishing operations were chosen (ISO S and ISO P grades), both with tool nose radius r_ε = 0.4 mm. The ISO S insert (TNMG 160404-SF 1115) has a coating PVD (Ti,Al)N+$(Al,Cr)_2O_3$ and a ultrafine grain (size < 0.5 µm) cemented carbide grade that adds wear resistance due to its hardness as shown in the Figure 1(a). According to the manufacturer, the coated compression tension also add toughness to the cutting edge and resistance against thermal cracking. Therefore, it is used in the turning of heat resistance super alloys with a cutting speed v_c = 65 m/min. The ISO P insert (TNMG 160404-LC 4315) has a coating CVD Ti(C,N)+Al_2O_3+TiN and a cemented carbide with grain sizes between 1 and 5 µm, as can be seen in Figure 1(b). According to the manufacturer, it has high wear resistance and excellent substrate adhesion. It is recommended to machine common steels that do not have heat treatments (i.e. low-alloy steels) with v_c = 555 m/min. Figure 1(c) shows the geometric and dimensional specifications for both inserts. The shank tool holder Sandvik DTJNL 2020 K16 (top and hole clamping method) was used as fixation system for both inserts.

As the workpiece material (AISI 4140) has a hardness up to 40 HRC, two smaller cutting speeds were used (60 and 120 m/min) in order to allow a longer machining time for experiment. Besides, two lubri-cooling conditions (dry and MQL turning) were tested. A a fresh tool edge was used in each of the 2^3 = 8 parameter combinations (two grade inserts, two cutting speeds and two lubri-cooling) in the tool-life tests of the ISO P and ISO S grade inserts. The other machining parameters used were depth of cut a_p = 0.3 mm and feed-rate f = 0.15 mm/rev.

MQL system consists of a mixture of lubricant plus compressed air. Then, the water-based synthetic oil Quimatic Jet was used as lubricant. Figure 2(a) shows the nebulizer Quimatic IV applied this mixture at a flow rate of 200 ml/h using a compressed air pressure of 400 kPa. The location of the sprinkler nozzle is an important factor in the effective application of the

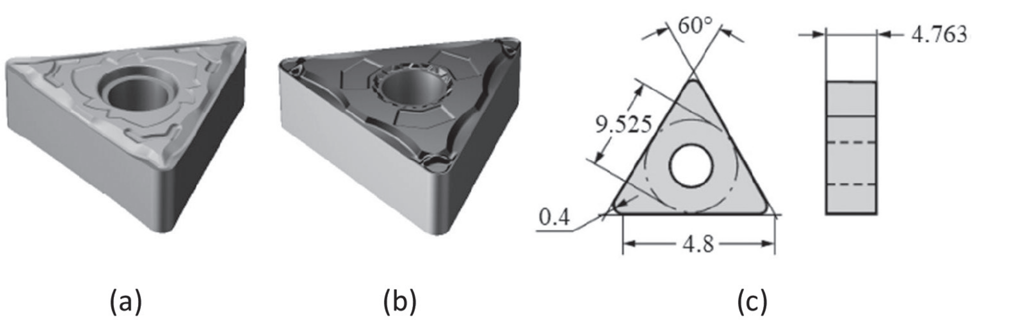


Figure 1. Inserts: (a) TNMG 160404-SF 1115; (b) TNMG 160404-LC 4315; (c) geometric and dimensional configuration for both.

Table 1. Chemical elements of AISI 4140 (%wt.).

C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	H	Others
0.40	0.23	0.85	0.02	0.02	1.01	0.18	0.18	0.01	0.15	1.40	1.09

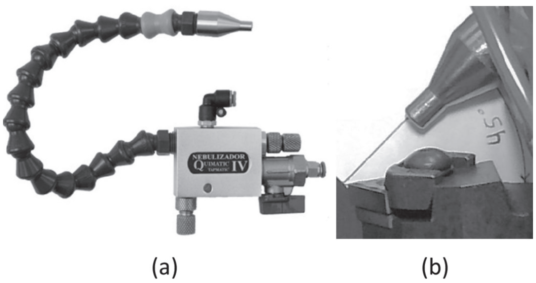


Figure 2. MQL system: (a) Nebulizer Quimatic IV; (b) Position of the nozzle at 45º.

oil mist; thus, the distance between the nozzle and the tool nose was fixed at 20 mm with 45º degree, as shown in the Figure 2(b).

Tool wear was measured using the USB Digital Microscope Dino-Lite model AM-413ZT, with a resolution of 1024 x 728 pixels and magnification of 50x. The tool wear image processing was made via Dino-Capture 2.0 software.

A maximum machined length of 3000 mm for each workpiece was determined for the criterion of tool-life, which was equivalent to 50 passes with L = 60 mm (75 mm initial and 45 mm final diameter). The tool nose wear (VB_C) was evaluated at each pass in the first five passes due to lack of literature information about the behavior of these insert grades in the hard turning. There was very small changes in wear at this stage, so measurements were taken every 5 passes (or 300 mm machined length) to reach VB_C^{3} 300 µm according to ISO 3685 [21].

The average roughness (R_a) of machined surface was recorded by rugosimeter Mitutoyo model SJ-201P with resolution of 0.01 µm and standard detector (diamond stylus with 5 µm tool nose radius) using sampling length l_r = 0.8 mm and evaluation length $l_n = 5 \times l_r$ = 4 mm. For each surface evaluated, three measurements on the R_a were made every 120º in each sample to assure a greater reliability.

RESULTS AND DISCUSSIONS

The inserts ISO-P and ISO S grades were evaluated comparatively for tool-life, tool nose wear and average roughness obtained over the lifetime.

Tool-Life and tool wear

ISO P grade

Figure 3 shows the tool wear versus machined length for Test 1 to Test 4.

The ISO P grade insert in dry turning with cutting speed v_c = 120 m/min (Test 1) reached the high

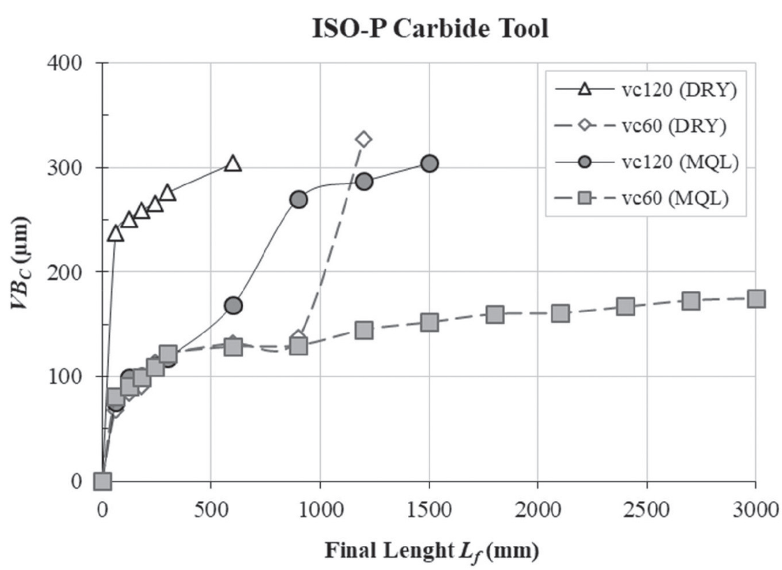


Figure 3. Tool nose wear versus machined length for the ISO P grade carbide insert.

tool nose wear $VB_C = 300$ µm in the low machining time $T_1 = 7.56$ min (and low machined length $L_{f1} = 600$ mm). This rapid increase in VB_C occurred prematurely in the first pass, probably due to the removal of the coating material from the tool rake surface. At this, the machining is performed by the substrate, which is less resistant. This causes tool wear to expand rapidly. This result was also cited by [22].

A 50% reduction of cutting speed ($v_c = 60$ m/min) in dry turning (Test 2) promoted a 283% increase in lifetime ($T_2 = 29$ min). However, when MQL turning at $v_c = 120$ m/min (Test 3), the lifetime had an 134% increase ($T_3 = 17.7$ min). Also, the lifetime under MQL turning at $v_c = 60$ m/min (Test 4) was $T_4 > 63$ min.

According to [20], the oil droplets applied by MQL causes a friction coefficient reduction in the tool-workpiece interface. This decreases the plastic deformations caused by high temperatures in the cutting-tool edge (which consequently increases tool-life).

Thus, although the ISO P grade coated carbide insert is recommended for the machining of ductile steels with relatively low hardness [13], the final tool nose wear in Test 4 was $VB_C = 175$ µm at the end of machined length.

Figure 4(a) shows the catastrophic tool failure (plastic deformation plus nose wear) that was resulted on the high temperature at cutting zone after dry turning using $v_c = 60$ m/min (Test 2). Comparatively, Figure 4(b) shows the tool nose condition after MQL turning at the same $v_c = 60$ m/min (Test 4), indicating the acceptable nose wear and oxidation marks.

Compressed air can carry more oxygen and nitrogen to the tool-workpiece interface as well as oil droplets in MQL turning. Thus, the oxidation of coating at tool nose is accelerate by abundant oxygen [23].

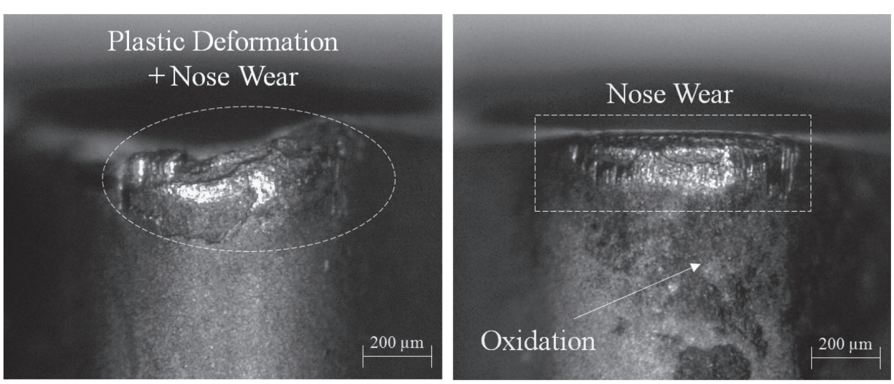
ISO S grade

Figure 5 shows the tool wear versus machined length for Test 5 to Test 8. All tests with the ISO S grade carbide insert showed that the nose wear was less than $VB_C = 150$ µm after machined length $L_f = 3000$ mm.

Although the difference between nose wear was minimal at the end of the experiments, in dry turning at $v_c = 120$ m/min (Test 5) the highest wear value was observed ($VB_C = 121$ µm) after $T_5 = 31.5$ min. For dry cutting with $v_c = 60$ m/min (Test 6), $VB_C = 107$ µm after $T_6 = 63$ min.

A low reduction of the final nose wear values is detected under MQL turning. For Test 7 ($v_c = 120$ m/min) the value was $VB_C = 93$ µm after $T_7 = 31.5$ min of machining and Test 8 ($v_c = 60$ m/min), $VB_C = 84$ µm after $T_8 = 63$ min.

Figure 6 shows that the wear values in the ISO S grade insert are very similar. In addition, it shows the presence of notch wear in these tests.



(a) Test 2 (b) Test 4

Figure 4. Tool edges worn ISO P grade for $v_c = 60$ m/min under: (a) dry turning; (b) MQL turning.

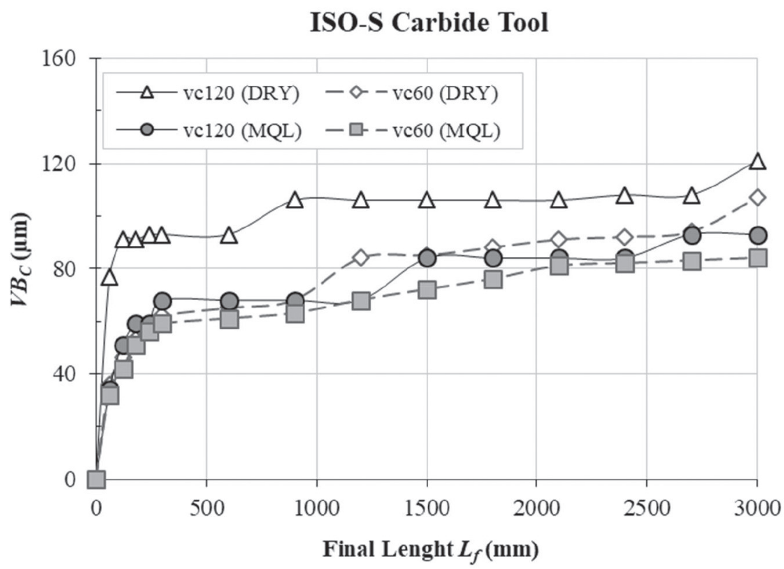


Figure 5. Tool nose wear versus machined length for the ISO S grade carbide insert.

The main mechanisms of notch wear are seizure/pull-out, diffusion and oxidation. The lubri-cooling conditions have a significant effect on the notch wear dimension. Tool cooling must be minimized and tool lubrication preferred to minimize notch wear. Thus, the MQL condition is adequate [24].

Figure 6(b) shows the presence of adhered material near to the secondary cutting edge that can be categorized as built-up edge (BUE). Under dry turning at v_c = 60 m/min, BUE did not occur with increasing cutting speed, as can be seen in Figure 6(a), or with the use of MQL turning at the same cutting speed (v_c), as shown in the Figure 6(c). In [25], the authors cited that BUE decreases with the increase v_c due to the softening of the chip and its removal by high sliding speed. Furthermore, the amount of temperature and friction coefficient reduction by MQL application allowed a reliable chip-tool interaction and elimination of BUE.

Comparative analysis

The visible superiority of the ISO S grade coated carbide insert in comparison to ISO P grade insert can be related to its ultrafine grains size, which tends to increase the wear resistance as well as the toughness of the cutting edge.

According to manufacturer (Sandvik), the ISO S grade insert has PVD oxide coating, which promotes chemical inherence and improved crater resistance. This inherency prevents the chemical interaction of

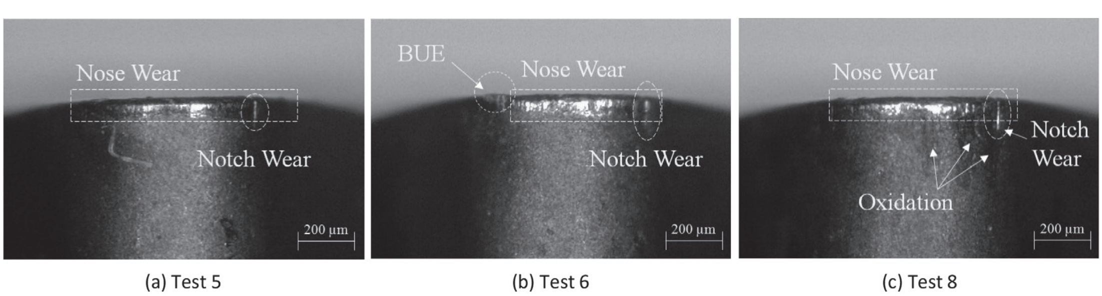


Figure 6. Worn edges of the ISO S grade carbide insert: (a) v_c = 120 m/min under dry turning; (b) v_c = 60 m/min under dry turning; (c) v_c = 60 m/min with MQL turning.

cutting tool constituents with workpiece surface and cutting fluid (diffusion), and protects against oxidation resulting from high temperatures combined with the presence of air and water.

Concerning to grain size, [26] reported that the lower grain sizes and the smaller percentage of binder, the harder the carbide insert grades. In addition, the lower grain sizes, the higher the thermal conductivity. The reduction in the grain size of carbide inserts also allows greater the cutting edge microchipping resistance.

Surface Roughness

Several studies [1, 4, 5, 7, 8, 19] cited the feed-rate as the main significant factor on the machined surface roughness. As the feed-rate is the same for all tests of this research, the influences of the cutting speed, tool nose radius and tool failures remains to be known.

ISO P Grade

Figure 7 shows the average surface roughness (R_a) values measured after machining with ISO P grade coated carbide insert. The R_a values represent the arithmetic mean of three measurements above cited.

The R_a increase with increasing tool nose wear (VB_C) due to enlarged friction at the tool-workpiece interface. The tool nose radius (r_ε) increase with increasing VB_C, and R_a reduces when r_ε increased. According to distinct researchers, R_a values tend to increase when the friction at the tool-workpiece interface leverages more than the growth of r_ε [7, 8]; R_a decreases when the effect of the r_ε increase overlaps with the friction's effect [27]; and R_a remains almost constant when friction does not predominate over the increase of r_ε (steady state) [12].

Test 1 (dry turning with v_c = 120 m/min) generated premature tool failure (accelerated wear) which increased intensely r_ε during the first pass. This caused a large decrease of R_a value.

Test 2 (dry cutting and v_c = 60 m/min) showed a continuous elevation of R_a with uniform increase of VB_C (up to L_f = 900 mm) and, at the end of tool-life, a large reduction in R_a (due to accelerated tool nose wear).

Test 3 (MQL machining using v_c = 120 m/min) showed a continuous growth of R_a with the constant increase of VB_C (up to L_f = 600 mm); after that R_a decreases (600 mm < L_f < 900 mm) and then increments again (L_f > 900 mm). This R_a reduction corresponds to the moment at which the accelerated tool nose wear occurred and thus increased the tool nose radius (r_ε).

Test 4 (MQL turning and v_c = 60 m/min) shows a growing increase in the R_a values, then an

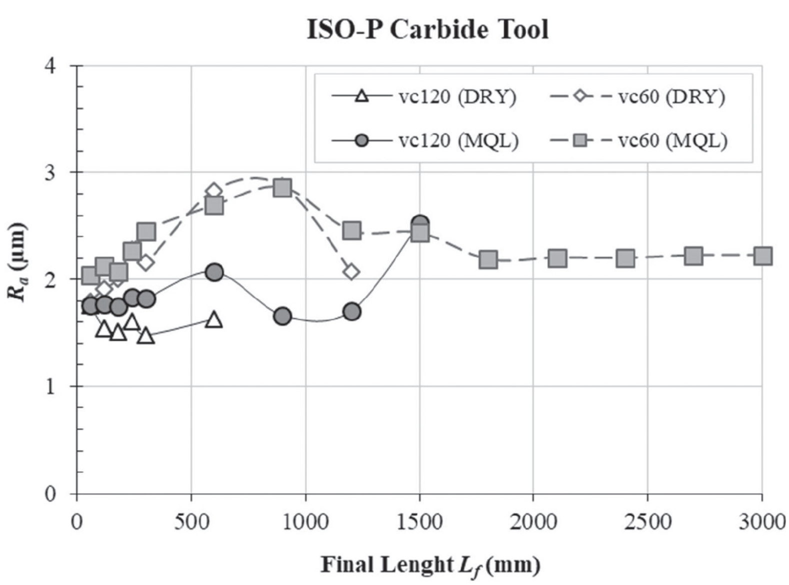


Figure 7. Average roughness for ISO P grade carbide insert.

abrupt reduction, followed by a steady state (after L_f = 1800 mm) with the constant increase of VB_C. In this case, there was no accelerated tool wear.

Besides that, higher cutting speed (v_c) gives lower average surface roughness (R_a) values for L_f < 500 mm, because of the increase in the cutting temperature causes a reduction in the shear strength of the workpiece material. Then, the machining forces are reduced and consequently the finishing is improved. The result is in accordance with [28].

Figure 8(a) and 8(b) show the tool nose radius (r_ε) recorded after dry and MQL turning using v_c = 120 m/min (corresponding to Test 1 and Test 3). Comparatively to the initial value ($r_{\varepsilon i}$ = 0.4 mm), the final values of tool nose radius were $r_{\varepsilon f}$ = 0.59 mm (increase of 47.5%) and $r_{\varepsilon f}$ = 0.44 mm (increase of 10%), respectively.

As mentioned by [27], a higher tool nose radius may provide a less roughness.

ISO S grade

Figure 9 shows the average roughness (R_a) values measured after turning with ISO S grade carbide tool insert in which the R_a maintains some stability over the machined length of 3000 mm (50 passes

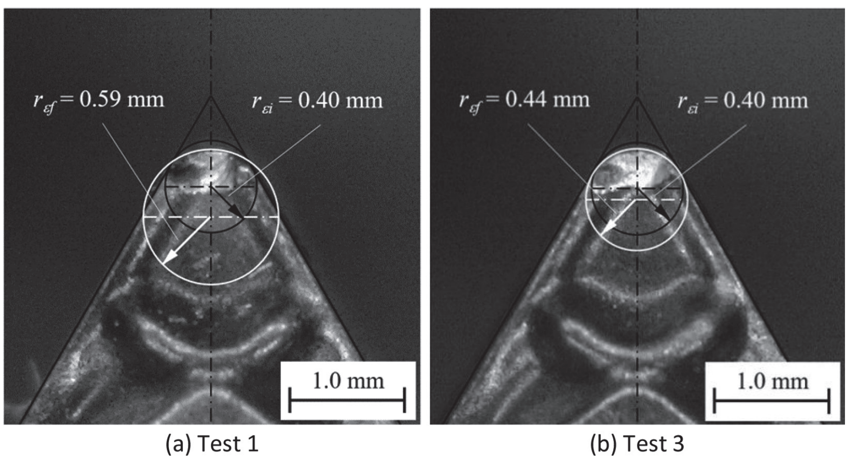


Figure 8. Increase of tool nose radius with v_c = 120 m/min on (a) dry turning; (b) MQL turning.

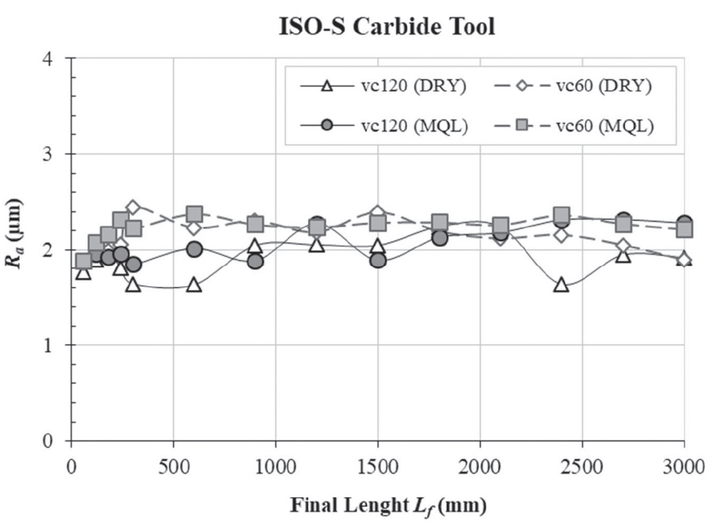


Figure 9. Average roughness for ISO S grade carbide insert.

of 60 mm). The R_a values represent the arithmetic mean of three measurements mentioned above.

The generated R_a consist of similar values with small variation [(2.09 ± 0.31) μm] in all tests (Test 5 to Test 8), since the nose wear (VB_C), notch wear and the presence of the built-up edge (BUE) were not sufficient to damage the machined surface roughness of the workpiece. Therefore, there was no predominance of friction on the increase of tool nose radius (r_ε). The result agrees with that obtained by [12].

Comparative Analysis

Higher VB_C - resulting from higher v_c - can increase R_a values and/or increase r_ε - which promotes a reduction in R_a (Figure 10). In this case, the VB_C was more intense and the variation of R_a was more significant in the ISO P insert (unstable VB_C) compared to the ISO S (stable VB_C).

The application of MQL tended to generate higher R_a values. This occurred because a certain reduction in temperature at cutting zone enabled a small reduction in wear rate and made the tool nose radius does not increase significantly. However, according to [24], the notch wear can have influence on the surface roughness of workpiece.

CONCLUSIONS

The following conclusions can be pointed out for the hard turning of AISI 4140 with coated carbide inserts ISO P and ISO S grades under machining conditions used in this work:

- The ISO P grade insert reached the maximum machining length (3000 mm) only in the MQL turning using v_c = 60 m/min (Test 4), with tool nose wear VB_C = 175 μm and average roughness R_a = (2.32 ± 0.54) μm at the end of tool-life. In the other tests, the insert reached VB_C > 300 μm before the machined length of 3000 mm.
- R_a values increased with the growth of VB_C on the machined surface with ISO P grade insert; however, the surface roughness decreased for high wear rates because there was increased tool nose radius (r_ε). This constant change in VB_C generated large variations of R_a values.
- The ISO S grade insert achieved the maximum machining length (3000 mm) in all tests; after dry turning using v_c = 120 m/min, the maximum VB_C = 121 μm; by MQL turning with v_c = 60 m/min, the maximum R_a = (2.23 ± 0.35) μm.
- On the surface machined with the ISO S grade insert, the R_a values remained stable in all tests; this stability is justified by the small variation of VB_C. However, there was notch wear in all tests, which may have affected the R_a values.
- The ISO S grade insert after tool-life of 31.5 min under MQL turning with v_c = 120 m/min presented VB_C = 93 μm and surface roughness R_a = (2.06 ± 0.25) μm. Thus, this is the best combination among those tested.
- The lowest values of R_a were found in situations with dry turning and/or v_c = 120 m/min. However, these machining conditions cause higher temperature at cutting zone, higher tool wear rate and higher tool nose radius (r_ε).

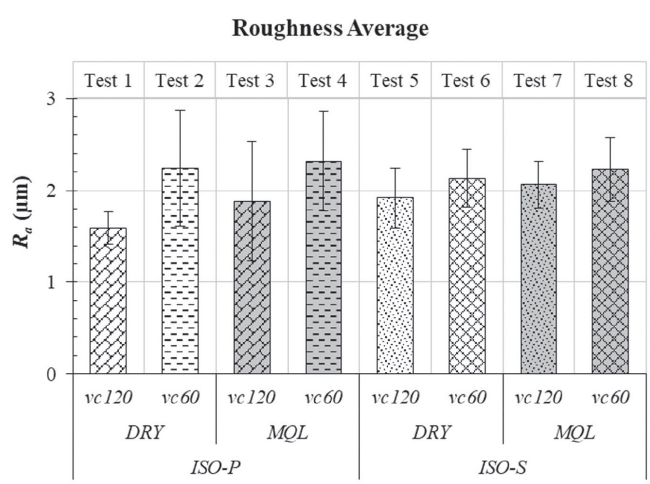


Figure 10. R_a values obtained in the tests.

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