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ORIGINAL ARTICLE

Tool life and wear mechanisms during Alloy 625 face milling

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Abstract Nickel-based alloys, particularly Alloy 625, are very important materials which have been increasingly used in applications that require wear resistance, particularly in the oil and gas industries. One of their characteristics is low machinability, which is due to their combined properties of high-temperature hardness, mechanical strength, and corrosion and wear resistance. These properties mean that low cutting speeds are needed in order to increase tool life, although this is not always achieved. The main goal of this work is to evaluate different cemented carbide grades, cutting speeds, and feed per tooth rates, aiming to determine the best condition for face milling of nickel-based 625 superalloy. The tool life performance of the cutting tools and the wear mechanisms were analyzed based on the results of milling tests using a cutter with cemented carbide inserts. The main results indicate that tool wear mechanisms in the Alloy 625 milling are similar to those that occur in other nickel-based superalloys, such as 718 and 713. However, the wear rate is lower and there is evidence of occurrence of oxidation wear.

Keywords Inconel 625 · Nickel-based alloys · Tool life · Wear mechanisms · Milling

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1 Introduction

Deepwater oil and gas sources have been growing and currently account for about 6 % of global oil production. Many countries are involved directly in this type of exploration, including Brazil, Canada, China, and India [1]. Other countries may be interested in having their own oil companies drilling in their territory. These oil sources have become so essential today that Brazil, for instance, now ranks in second place among the countries that invest the most in increasing production, and is outranked only by Iraq [2], which produces four times more than it did two decades ago [3].

The aforementioned sources, which consist predominantly of oil, are concentrated in countries that are not members of OPEC and are therefore crucial to the future outlook of the global economy. However, there still are infrastructural and economic constraints for their exploration [4], including problems involving the manufacture and conservation of oil drilling machinery, particularly with respect to mechanical properties and corrosion resistance.

Nickel-based superalloys are an unusual class of metallic materials with an exceptional combination of high-temperature strength, toughness, and resistance to degradation in corrosive or oxidizing environments [5]. Therefore, superalloys are extensively used in the aerospace industry, particularly in the manufacturing of gas turbine compartments, as well as in marine equipment, nuclear reactors, pulp and paper, petrochemical plants, and food processing equipment [6]. One of the most important properties of these alloys is their high corrosion resistance [7], which is essential in the oil and gas industries, since the equipment is employed in highly corrosive environments.

However, the machinability of nickel-based alloys is low, i.e., only 8 to 20 % that of ordinary carbon steel, resulting in relatively inefficient processes, in which, frequently, wear is considered the main limiting factor for the process [8]. The poor machinability of these alloys is the result of their inherent characteristics, such as high-hardness and high-temperature mechanical properties, high shear stresses during the cutting process, high work hardening, the presence of abrasive carbides in the matrix, low thermal conductivity, and welding of the chip on the cutting edge [9]. Therefore, cemented carbide, cBN, or ceramic cutting tools, coated or uncoated [8], are subject to high wear rates, which shorten the tool life.

Among all the nickel-based alloys, the Alloy 625 presents the desirable properties for oil drilling environments, particularly high resistance to pitting and stress corrosion [10]. Alloy 625 offers excellent weldability and hot cracking resistance and is one of the few alloys manufactured today, for which the ASME's Boiler and Pressure Vessel Code has defined allowable design stresses for service up to 982 °C [11]. Thus, several shipboard components, springs, seals, connectors, screws, rivets, flexure devices, and welded coatings (tubes, blinds, tees, elbows, valves, manifolds, etc.) have been employed in this material as base [11–13]. Fusova et al. [14] investigated the wear mechanisms that occur during the dry turning of Alloy 625 in three different conditions (vacuum induction melting, vacuum arc remelting, and forging followed by soft annealing), using cutting speeds of 40 to 300 m/min; depths of cut of 0.05, 0.10, and 0.15 mm; and cemented carbide cutting tools. However, they only performed one pass and did not carry out tool life tests. In these tests, the authors observed that increasing the depth of cut increases the tool wear rate, while increasing the cutting speed decreases the wear rate. There are no other published studies about the tool wear mechanisms in machining Alloy 625, specifically. However, other studies on nickel alloys have found that increasing the cutting speed tends to increase the tool wear rate [6, 15–18].

The increase of tool wear rates is intrinsically related with increase in cutting temperature [8, 19–22], and higher temperatures tend to favor wear mechanisms and reduce the mechanical strength of tools.

Bhatt et al. [23] investigated the tool wear mechanisms that occur during the turning of Inconel 718, using different feeds and cutting speeds, and they found that the predominant mechanisms during the process were abrasive and diffusive wear. In their tests, a triple-layer coated cemented carbide tool presented good performance at high cutting speeds and low feed rates, while a single-layer coated tool performed better at low cutting speeds and intermediate feed rates.

The purpose of this study is to fill a gap of investigation in the tool life and wear mechanisms of a nickel-based superalloy (Alloy 625) during machining.

2 Experimental setup

Figure 1a depicts the workpiece used in the step 1 of this study, a 300 mm×200 mm×25.4 mm (for the step 2, the dimensions were changed to 200 mm×200 mm×25.4 mm) AISI 8630 steel plate coated with six weld-deposited layers of nickel-based Alloy 625 (44 HR_C). The cladding was about 20 mm thick and was deposited according to the following process parameters:

- Welding current 140 to 150 A
- Input voltage 24 to 26 V (DC)
- Electrode feed rate 250 to 325 mm/min
- Electrode Alloy 625 with 4.0 mm gauge

Cooling of the coated layer was controlled by a thermal blanket, since no stress relief heat treatment was applied, which is the case in industrial settings. The micrographs in Fig. 1b, c show two different regions of the cladding.

The cutting tool was an ISCAR HM90 F90AP-D63-7-22 face mill whose cutting angles are described in Table 1 (data measured in a Mitutoyo's 3D Beyond-Crysta 710 coordinate measuring machine (CMM)). The tool holder was a DIN 69871 Form A/DIN 6358 SK 50.

Table 2 describes the main characteristics of the ISCAR HM90 APCR 100304 PDFR-P cemented carbide inserts after their assembly in the tool holder. These angles were also measured based on the abovementioned Mitutoyo CMM.

The experimental tests were carried out in an Okuma MB 56-VB vertical machining center operating at a nominal power of 18 kW. The workpiece was fixed at eight equidistant points around its edges, as illustrated in Fig. 2.

Houghton HOCUT 795 semi-synthetic cutting fluid (8 % concentration and 0.022-m^3/min flow rate) with extreme pressure (EP) additives was applied through four nozzles, three

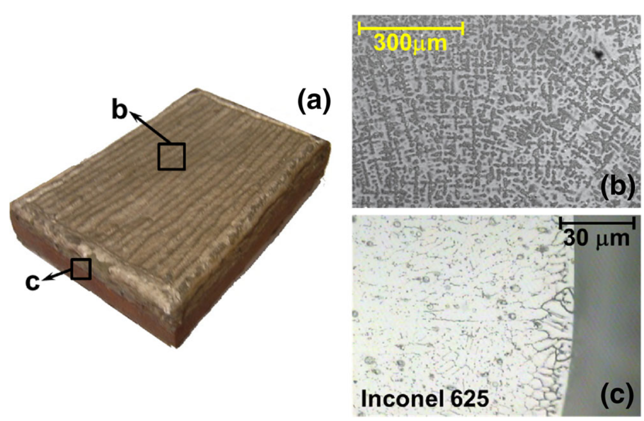

Fig. 1 **a** Workpiece used in the tests (base metal + cladding). **b** Micrograph of the dendritic structure of the strained material. **c** Micrograph of the transition region between Alloy 625 and AISI 8630 steel

Table 1 Angles of the carbide inserts in the face milling cutter

Angle	
Radial rake angle	−3° 55′
Axial rake angle	9°

positioned around the milling cutter, and the fourth one directed toward the workpiece, aiming to keep the cutting region continuously immersed in cutting fluid.

2.1 Research strategy

The machinability of nickel-based superalloys is poor, including that of Alloy 625; therefore, they present very short tool lives (of a few minutes). Moreover, the main component of these alloys is nickel, which is very expensive, thus representing a very high workpiece cost. Hence, efforts should focus on reducing the amount of process losses as much as possible.

In this regard, this work was designed to determine the best milling condition in a pre-established series, based on the manufacturer's recommendations, and using as few workpieces as possible.

The work involved performing tool life tests applying the machining conditions recommended by the manufacturer and comparing the performance of different carbide grades and cutting fluid conditions. The objective was to gain a better understanding of the tool wear mechanisms of the tool carbide grades that performed well in machining Alloy 625. To this end, this work was performed in two steps (see Fig. 3), which are described in detail below. It is worth to mention that, in both steps, the face milling feed direction was the same as the welding direction.

Table 2 Characteristics of the interchangeable inserts used in the tests

Characteristics	Value/type	Hardness (HRA)
Radial rake angle	23° 24′	–
Axial rake angle	14° 51′	–
Radial clearance angle	14° 55′	–
Axial clearance angle	2°	–
Tool nose radius (r_ε)	0.4 mm	–
Tool edge radius (r_n)	0.0000–0.0127 mm	–
Particle size	5~8 μm	–
Grades (uncoated)	Grade 1—IC 08 (ISO S10–S30)	91.90
	Grade 2—IC 28 (ISO S20–S25)	90.00
Grades (TiAlN/TiN PVD coated)	Grade 3—IC 908 (ISO S05–S20)	91.90
	Grade 4—IC 928 (ISO S15–S40)	90.00

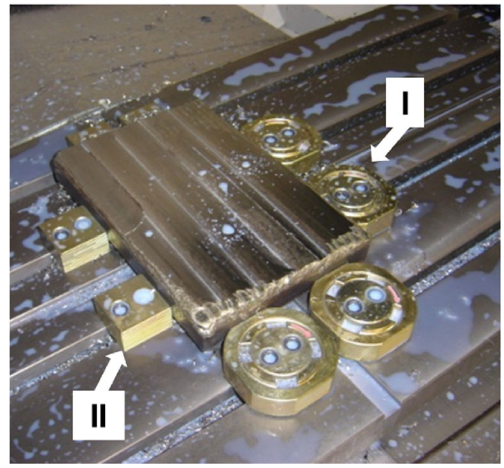

Fig. 2 Fixation of the workpiece on the table of the machining center, showing the four clamping points (I) and the four abutment points (II)

2.1.1 Step 1

Step 1 consisted in performing face milling tool life experiments using different cutting conditions, making a total of 32 tests, in order to determine which tool grade presented the best performance in milling the weld-deposited Alloy 625. In this

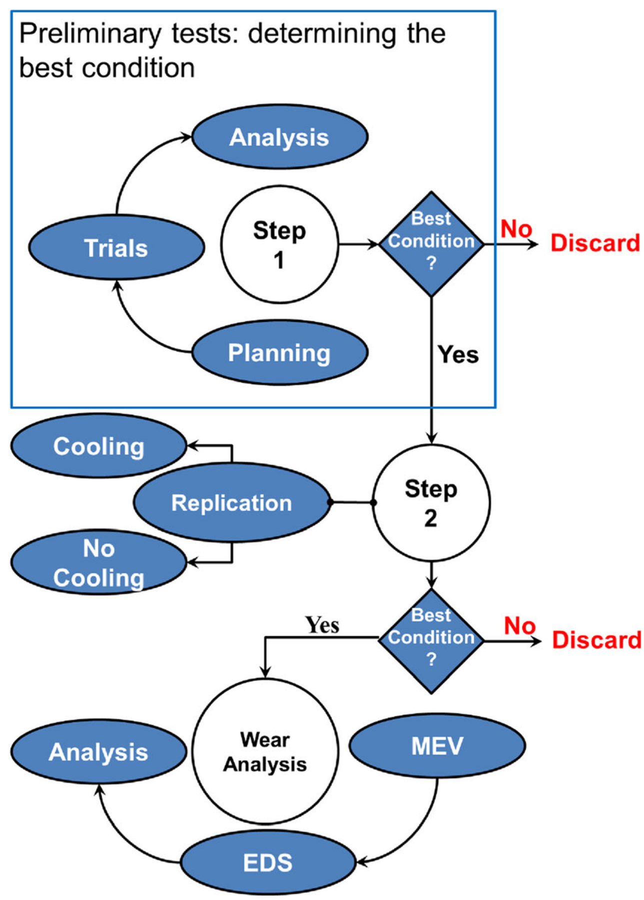

Fig. 3 Flowchart showing the two steps of the experimental tests, decision making, and analysis of the tool wear mechanisms

step, the tool holder, geometry of the inserts, axial depth of cut (a_p), cutting width (a_e), number of cutter teeth (z), and the applied cutting fluid were kept constant (see Table 3). The following variables were tested: cutting speed (v_c), feed per tooth (f_z), milling strategy, and insert grades (see Table 4).

The main objective of the first step was to identify the best set of parameters among the 32 tested. After identifying the best condition, the second step of the experiment was carried out, as explained in detail later.

The criterion adopted to determine the end of tool life was a maximum allowable flank wear (VB) of 0.3 mm (according to ISO 8688-2) or tool damage that would prevent the test from continuing (significant chipping or fracture). Moreover, for safety reasons, the machine tool cutting power was monitored by using its potentiometer, and the test was stopped as soon as 90 % of the available cutting power was reached.

In this step, tool wear was measured at intervals of 300 mm of linear feed length, using a magnifying glass with 8X magnification and 0.05-mm precision. In addition, the feed speed (v_f) was reduced by 30 % on the tool entrance into the workpiece, since some chipping of the inserts was observed in the preliminary tests. It should be noted that this procedure is performed routinely in industrial settings. At the end of this step, inserts from all the tested conditions were selected for a more in-depth wear analysis.

2.1.2 Step 2

After concluding step 1, monitoring and comparing the evolution of tool wear in each test, the best result in terms of tool life was chosen and its parameters were used in step 2 of the experiments.

The chosen parameters were IC928 grade, v_c of 30 m/min, f_z of 0.065 mm/tooth, application of flood coolant, and down milling.

In step 2 (Table 5), a dry milling test was performed to evaluate the influence of cutting fluid on tool life. The evolution of the wear of each insert was monitored in this step using a Leica optical microscope with 6.4 to 40X magnification, and the images were processed using Leica Qwin Pro version 2.2 software. In this step, measurements were taken at intervals of 200-mm feed length, thus allowing for more accurate predictions of trends along the tool life.

Upon the conclusion of step 2 and the analysis of tool life, the tool life curves were built for each milling cutter insert, scanning electron microscopy (SEM) micrographs were recorded, and the chemical composition of wear lands was analyzed via energy dispersive spectroscopy (EDS). This enabled possible wear mechanisms to be identified and explanations found as to why this configuration was the best.

Table 3 Constant parameters of the tests

Tool holder	HM90 F90AP-D63-7-22
Inserts	HM90 APCR 100304 PDFR-P
Diameter (mm)	63
a_e (mm)	42
a_p (mm)	2.0
z	7
Cutting fluid	Yes

Table 4 Variable parameters of the tests

v_c (m/min)	30 and 45
f_z (mm/tooth)	0.065 and 0.1
Strategies	Up and down milling
Grades	Grade 1—IC 08 (ISO S10–S30) Grade 2—IC 28 (ISO S20–S25) Grade 3—IC 908 (ISO S05–S20) Grade 4—IC 928 (ISO S15–S40)

3 Results and discussion

The analysis of the tests performed at cutting speeds of 30 and 45 m/min (see Figs. 4 and 5) led to the conclusion that, in general, the strategy of down milling was more advantageous for the two tested tooth feed rates and for all the tool grades (coated and uncoated). However, tool life was found to be generally much longer with the 0.065-mm tooth feed rate than with 0.1 mm. This can probably be attributed to the cutting characteristics, since the thickness of material removed by the tool during machining is greater at the higher feed rate. This increases the contact area at the tool/workpiece interface and probably causes greater tool heating, thus increasing the tool wear rate [24, 25].

Asymmetric and predominantly down milling, with the cutter diameter that was used here (1.5 times larger than the cutting width), tends to be better than predominantly up milling, because the insert enters the cutting zone more easily [26, 27]. In up milling, the tool enters the workpiece under high friction because, up to a given point, the material is only deformed, without forming chips. Conversely, in predominantly down milling, the tool enters more easily because the thickness of removed material is higher, but not so high due to the

Table 5 Summary of the conditions employed in the two tool life tests using the best result identified in step 1

Tool life test	Test conditions
1	Best result of step 1 with flood coolant
2	Best result of step 1 dry milling

feed per tooth used, so there is less friction, considering that the tool has enough shock resistance to receive impacts inherent to the milling process.

The performance of the tool grades differed significantly at the two tested feed rates. The higher cutting speed (45 m/min) drastically reduced the tool life, probably due to the low thermal conductivity of Alloy 625. The cutting speed strongly influences the cutting temperature and wear mechanisms, which will be analyzed later. Therefore, an increase of 50 % in cutting speed (from 30 to 45 m/min) is practically infeasible, probably because of the fact that in lower cutting speeds, a large temperature gradient is not observed from the surface to the subsurface of material [21].

It should be noted that one particular grade performed better at both cutting speeds (grade IC928−f_z=0.065 mm/tooth; highlighted in Fig. 4), while two other grades presented the worst performance at 45 m/min (IC28 and IC908−f_z=0.1 mm/tooth; highlighted in Fig. 5). Thus, it can be stated that the cutting speed (in the range tested here) did not exert a significant influence on the wear mechanisms in the tested grades, which are the same, corroborated by the images of the worn inserts (presented later herein) and the EDS analyses.

Also note that the uncoated tool grades (IC08 and IC28), even with relative poor performance, presented a considerably long life for f_z=0.065 mm/tooth, which was not expected since the coating plays a fundamental role in protecting the tool substrate and in reducing friction during cutting. For this reason, it was assumed that coated tools always perform better than uncoated tools, whose substrate is exposed, as reported by Prengel [28] and Ducros [29]. Furthermore, some results demonstrate that a coated tool resulted in reduction in microhardness in the surface and subsurface region, and, in the case of Inconel 825, CVD multilayer coating has synergistic influence on the improvement of the machined surface integrity [30]; thus, it can improve the tool performance.

The greater toughness of the substrate, allied to the quality of the tool coating (TiAlN), was the reason why grade IC928 showed the best tool life performance among the four tested grades. A similar finding can be observed upon examining the two uncoated grades (IC08 and IC28), since the toughest and least wear-resistant grade, IC28 (considering that Alloy 625 is highly abrasive and presents high work hardening), performed better than the more abrasive wear-resistant tool grade (IC08). This was probably because the main determining factor for the end of tool life was the shock the tool underwent in the milling process. In conclusion, it can be stated that the performance of the toughest tool grade was better than the others, both coated and uncoated tools, when operating at 30 m/min and 0.065 mm/tooth.

Some of the tested tools reached a tool life of almost or more than 30 min, and some of them reached almost 70 min. Tool lives that exceed 10–15 min are unusual when machining nickel-based superalloys. Therefore, tests were carried out with the tool grade that presented the longest tool life (highlighted in red in Fig. 4) to confirm and better evaluate the tool wear mechanisms involved, which were analyzed by SEM and EDS. The behavior of the tool during dry milling was also evaluated (see Fig. 6), in view of the relatively high cost of cutting fluids and their environmental impact. Another reason for carrying out this test was the much longer life of this tool, as well as its unusual behavior in machining the nickel-based superalloy.

In Fig. 6, note that during the repetition (v_c of 30 m/min, f_z of 0.065 mm/rot, and tool grade IC928), the test with flood cooling presented a similar tool life to the test carried out in

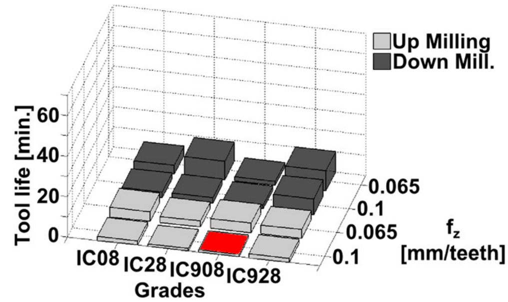

Fig. 5 Tool life tests using a cutting speed of 45 m/min, cemented carbide tools (different grades), predominantly down and up milling, and flood application of cutting fluid (step 1)

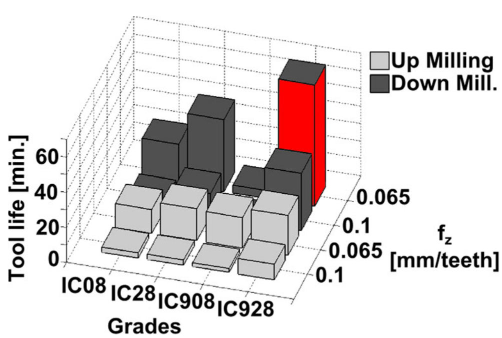

Fig. 4 Tool life tests using a cutting speed of 30 m/min, cemented carbide tools (different grades), predominantly up and down milling, and flood application of cutting fluid (step 1)

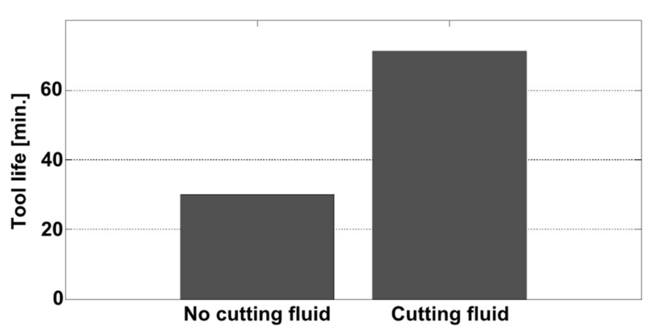

Fig. 6 Tool life tests performed at a cutting a speed of 30 m/min, step 2, corresponding to the repetition of the best condition identified in step 1, without cutting fluid

step 1, i.e., slightly more than 70 min. This was not the case when dry milling was tested, resulting in a considerable decrease in tool life, which reached about 30 min. Therefore, the cooling effect of cutting fluid is crucial to the good performance of the cutting tool. Even so, the tool life attained by the best test configuration (tool grade and cutting conditions) in dry milling was much longer than the tool life usually achieved in machining nickel-based alloys with cemented carbide tools. In fact, the tool life achieved without cutting fluid (in the conditions tested here) was one of the three longest lives achieved in all tests. Thus, if only the cost of the milling process were analyzed, dry cutting could be considered a feasible option, in view of the higher costs involved in the purchase, treatment, and disposal of cutting fluids compared to the cost of the cutting tool. However, the milled surface integrity should be evaluated to confirm the technical feasibility of dry cutting.

Another analysis that should be done is whether the milling operation in question is a bottleneck process. If it is not, it is possible that more time will be spent in changing the cutting tool, so dry milling could be used. Conversely, if the operation is a bottleneck process, then the best choice is to use flood cooling to the increase tool life and reduce the number of tool changes. This is significant because flood cooling requires only a half of tool changes than the dry milling.

3.1 Analysis of tool wear mechanisms

3.1.1 Tests with flood cooling (steps 1 and 2)

The toughest grade used in the tests (IC928), which presented the longest tool life of about 70 min, did not presented fractures (e.g., chipped, cracking, or breakage) during machining; therefore, it was able to withstand the shocks inherent to the milling process. The SEM and EDS analyses (see Fig. 7) of the tool flank surface (Fig. 7b) revealed the presence of elements such as Ni and Cr, evidencing adhesion of workpiece material near the cutting edge. Co and W originating from the tool substrate were also present in the same region near the cutting edge (point 1—Fig. 7b). This fact, allied to the rough aspect of the region in question, may indicate tearing of the coating and tool material. Another important element identified at point 1 was oxygen, which indicates possible oxidation, a typical wear mechanism in the machining of nickel-based alloy [8]. Point 2 (Fig. 7b) shows Ni, Cr, and larger amounts of Fe and Nb from the workpiece material, as well as Co and W from the tool substrate, indicating workpiece material adhered to the tool surface, as well as the fact that the substrate was already exposed.

At point 3 (Fig. 7b), note the predominant presence of the coating elements (Al and Ti), and very small amounts of elements from the workpiece material (Cr and Ni), indicating that this region was not worn and that there was little adhesion of workpiece material at this point.

Figure 8 shows the rake face of the cutting tool depicted in Fig. 7. An analysis of Fig. 8 reveals four different situations, similar to what were observed on the flank face. Point 1 shows elements from the coating (Al and Ti), indicating that this point was not worn. Point 2 is a region of transition containing elements from the workpiece material (Cr, Ni, and Fe) and from the coating (Al and Ti). Point 3 contains a large amount of Alloy 625 (Cr, Ni, and Fe) and few elements from the tool substrate (Co), suggesting that a large quantity of material was adhered in this region. On the other hand, point 4 shows little adhered material, since it contains low contents of Cr, Fe, and Ni and a high content of W, indicating exposure of the substrate. In addition, the presence of oxygen is visible at points 1 and 4, making the occurrence of oxidation a plausible hypothesis.

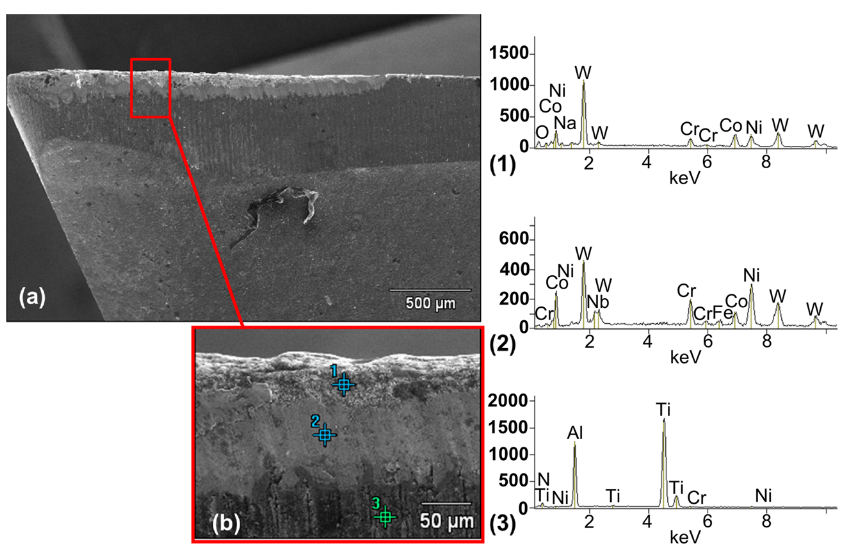

Fig. 7 Flank surface of one of the worn grade IC928 inserts (v_c of 30 m/min, f_z of 0.065 mm/tooth, and flood cooling)

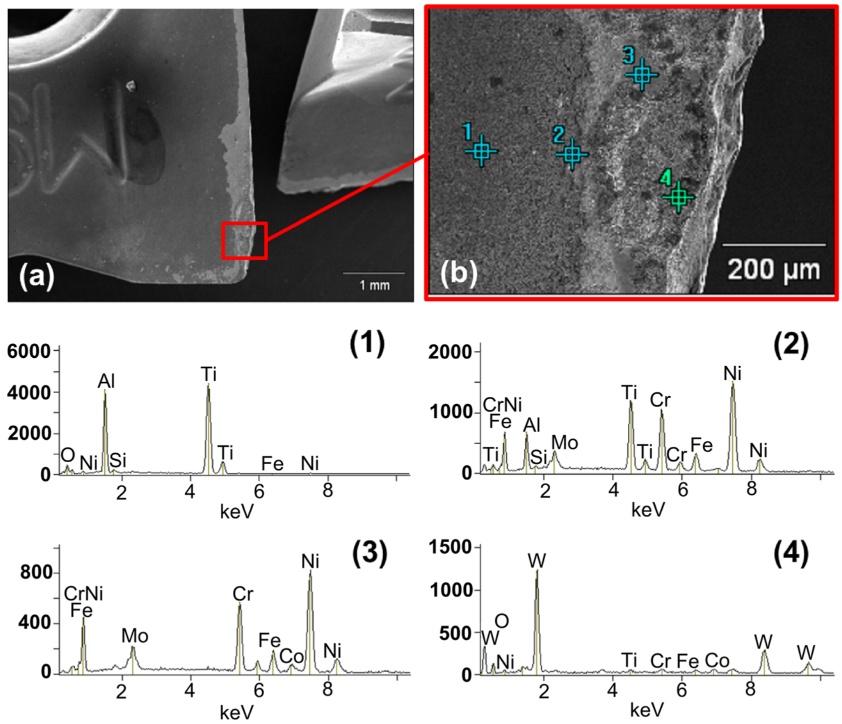

Fig. 8 Rake surface of a worn tool (v_c of 30 m/min, f_z of 0.065 mm/tooth, and flood cooling)

Upon evaluating the tool grade that presented the worst tool life, i.e., IC28 (see Fig. 9), it can be stated that most of the grades did not withstand the cutting forces and/or temperatures and were fractured during the milling operation. This macrocracking of the cutting tool determined its end of life. Among the tested grades, grade IC28 showed the lowest toughness, which is why the inserts of this grade failed catastrophically. An analysis of the SEM and EDS micrographs indicated two main and distinct regions on the tool's flank face, represented by points 1 and 3 (Fig. 9c). The region at point 1 contains a large amount of adhered workpiece material (with the presence of Ni, Cr, Fe, and Mo). On the other hand, the region at point 3 shows considerable amounts of W and Co, evidencing the exposure of the tool's substrate, as well as the presence of Al, possibly due to the partial removal of the tool's coating. The micrographs in Fig. 9b—region of point 3, and Fig. 9c reveal that part of the tool material seems to have been torn away abruptly from the surface, exposing the substrate of the cemented carbide insert, presumably due to the impact (lack of toughness) or sequence of impacts (fatigue or fast nucleation and propagation of cracks) the tool underwent during the entry and/or exit of the cutter. Lastly, point 2 in Fig. 9b indicates that the coating was partially removed even in a region far from the broken region like point 2, since there is a visible presence of W and Co from the substrate and Al from the coating. In addition, it should

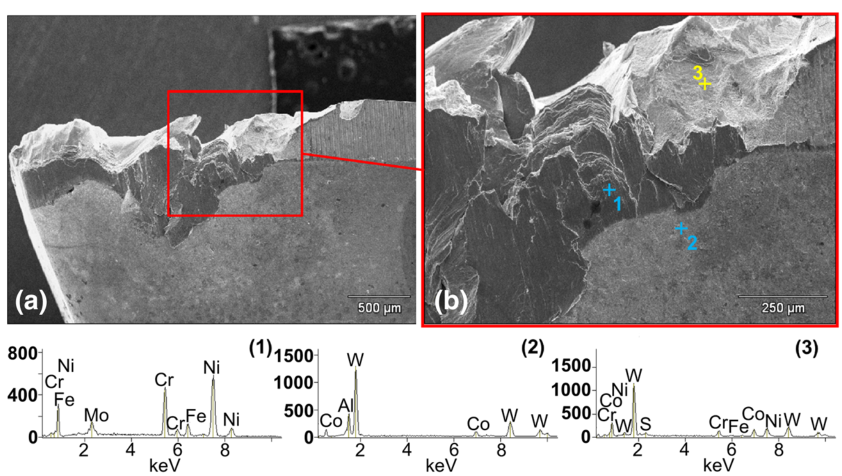

Fig. 9 Insert after milling in the conditions that presented the lowest tool life (v_c of 45 m/min, f_z of 0.1 mm/tooth, and grade IC28)

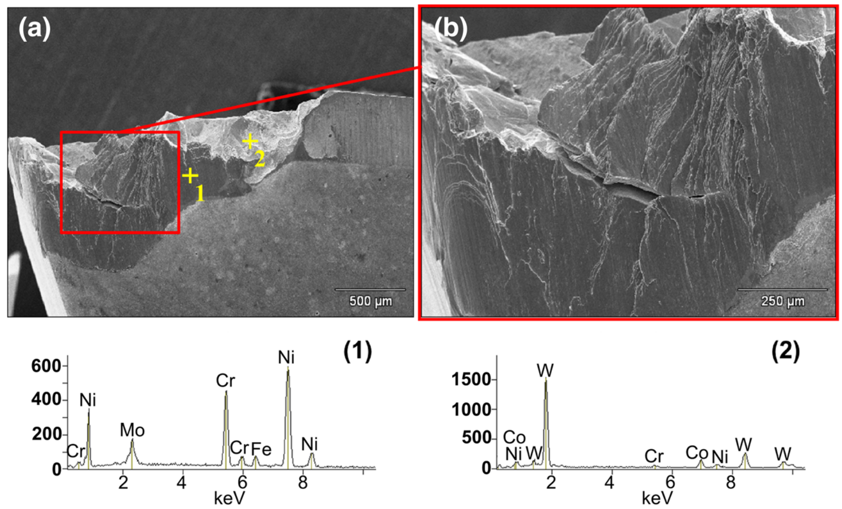

Fig. 10 Another insert used in the test that presented the lowest tool life (v_c of 45 m/min, f_z of 0.1 mm/tooth, and grade IC28)

be noted that the original cutting edge disappeared completely.

Figure 10 shows another insert used in the test that presented the lowest tool life, where it is possible to note the presence of a crack in the chip adhering to the tool surface. This crack was probably caused by the high level of compression imposed on the chip. The appearance of points 1 and 2 in Fig. 10 is similar to that of points 1 and 3 in Fig. 9. The analysis of the phenomena involved is also similar.

3.1.2 Dry milling test (step 2)

The degradation of the tools, in the different grades and which have the better and worst results, was completely different. Nickel superalloys have the feature to be quite severe with the tools, with regard to the tool wear. Therefore, it was decided to test coated and uncoated grades. The coating can protect the substrate and ultimately increase the tool life, but there is a possibility of a better performance in the case of a sharper edge tool usage with uncoated tools, since the nickel superalloys have the characteristic of high strain hardening.

The coated tools have presented different initial wear mechanisms (e.g., adhesion and oxidation), culminating in attrition at the end of the process. Thus, tool elements pull off the substrate and/or coating, eventually, induce abrasion on the surface by attrition. In the other hand, the uncoated tools, despite the higher toughness and sharper edge, do not resist to mechanical and thermal stresses and ended up fracturing.

The test performed under the conditions that presented the longest tool life (grade IC928, v_c of 30 m/min, f_z of 0.065 mm/tooth, and down milling) without cutting fluid reduced the tool life by about 50 %. However, the wear mechanisms remained the same obtained in the experiment with cutting fluid and the same tool and cutting conditions, with a large amount of Alloy 625 adhered to the tool surface (point 1, Fig. 11b). The absence of cutting fluid did not change the wear mechanisms, and temperature was the determining factor for the increase in wear rate. This region did not contain elements from the substrate or the coating. It should be noted that, despite the substantial amount of adhered material, the cutting edge was not fractured, unlike the edge shown in Fig. 9. Nevertheless, the substrate at point 2 was exposed, as indicated by the presence

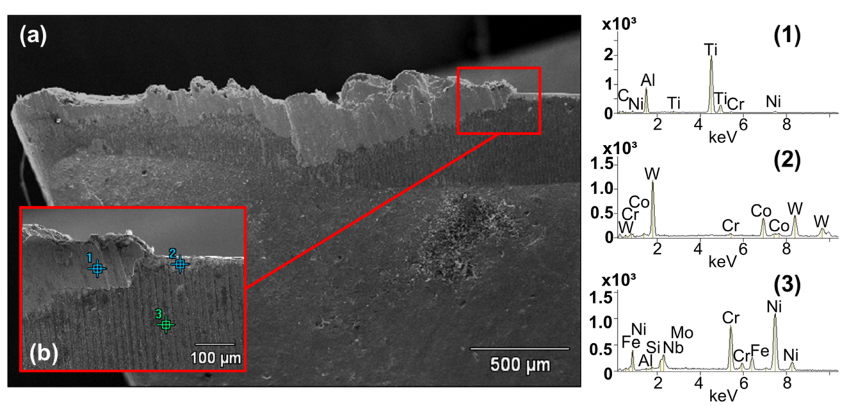

Fig. 11 Image of a worn tool using in dry milling (v_c of 30 m/min, f_z of 0.065 mm/tooth, and grade IC928)

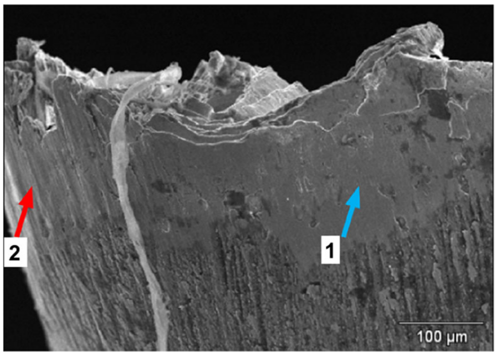

Fig. 12 Detail of a tool nose (flank face) damaged in the dry milling test, apparently due to abrasive wear

of W and Co. A small amount of workpiece material is also visible in this area, indicating some adhesion. Another important finding is the difference in the surface aspect of the two regions (points 1 and 2), with the former showing a smooth aspect and the latter a rough one with the presence of grooves and some adhered material. Lastly, point 3 (Fig. 11b) resisted the process of tool degradation, since the tool coating remained intact. This was confirmed by an EDS analysis, although small amounts of workpiece material were also adhered in this region.

Figure 12 shows details of a worn insert used in dry milling, revealing a region of the tool flank face apparently containing workpiece material adhered to the surface, which appears to have been formed in various layers (indicated by a blue arrow). In addition, there are grooves close to the tool nose (red arrow), which are parallel to the cutting direction on the adhered material, indicating the occurrence of abrasion during milling, common in the milling of Inconel 718 [31], for example.

Figure 13 shows the rake face of the cutting tool (grade IC928—dry milling). In this figure, note that the tool substrate is exposed in the region of point 1, with the presence of a small amount of elements from Alloy 625. Moreover, points 2 and 3 contain only elements from the workpiece material adhered to the tool rake surface. These evaluations indicate that the entire surface (regions of points 1, 2, and 3) was degraded and that probably no coating was left under the adhered material but only substrate. The adhesive wear mechanism was present, and some oxidation possibly occurred, since the presence of oxygen was detected at points 1 and 3.

4 Conclusions

The tool wear mechanisms in the Alloy 625 milling are similar to those that occur in the other nickel-based superalloys, such as 718 and 713. However, the wear rate is lower, considering the grade (IC928) with better results presented in this work and there is evidence of occurrence of oxidation wear. Thus, it is possible to affirm that at equivalent machining conditions, Alloy 625 can enable greater productivity.

Other general conclusions:

- Down milling is more advantageous for tool life than up milling, indicating that the cutting tool can withstand impacts better than friction.
- In down milling, the cutting conditions that generated the lowest impact energy (f_z of 0.065 mm/tooth and v_c of 30 m/min) favored tool life.
- The toughest tool grade (IC928) presented the longest tool life, probably because it is better able to withstand impacts during milling.
- The absence of cutting fluid decreased the tool life, although the wear mechanisms remained unchanged.
- The main wear mechanism acting in the process was adhesive wear that leads to attrition wear.
- There are indications of the presence of abrasion, evidenced by grooves parallel to the cutting direction, as well as oxidation due to the presence of oxygen in some EDS analyses.

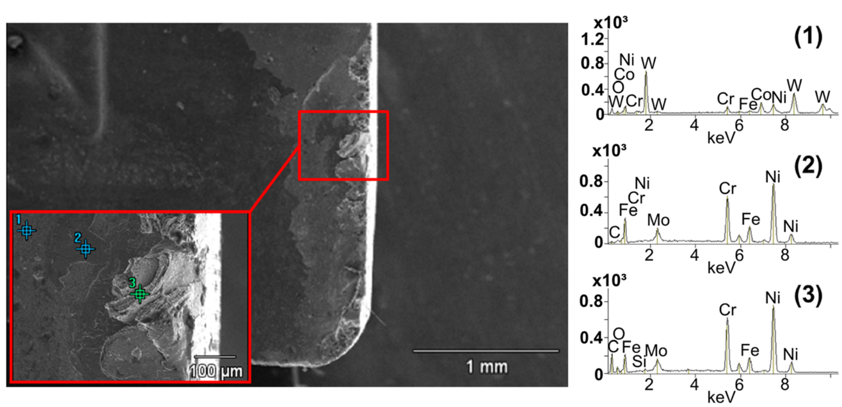

Fig. 13 Rake surface of a worn insert used in the dry milling test

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