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Wear and MnS Layer Adhesion in Uncoated Cutting Tools When Dry and Wet Turning Free-Cutting Steels

D. Martinez Krahmer [1,2,*], S. Hameed [3], A. J. Sánchez Egea [4,*], D. Pérez [1,2], J. Canales [5] and L. N. López de Lacalle [5]

1 Center for Research and Development in Mechanics, National Institute of Industrial Technology (INTI), Avenida General Paz 5445, 1650 Miguelete, Provincia de Buenos Aires, Argentina; danielap@inti.gob.ar
2 Faculty of Engineering, Universidad Nacional de Lomas de Zamora, Juan XXIII y Camino de Cintura, 1832 Buenos Aires, Argentina
3 Department of Mechanical Engineering (EPSEVG), Universitat Politècnica de Catalunya, Av. de Víctor Balaguer, 1, Vilanova i la Geltrú, 08800 Barcelona, Spain; hameeds@tcd.ie
4 Department of Mechanical Engineering (EEBE), Universitat Politècnica de Catalunya, Av. Eduard Maristany, 16, 08019 Barcelona, Spain
5 Department of Mechanical Engineering, Aeronautics Advanced Manufacturing Center (CFAA), Faculty of Engineering of Bilbao, Alameda de Urquijo s/n, 48013 Bilbao, Spain; javier.canales@ehu.eus (J.C.); norberto.lzlacalle@ehu.eus (L.N.L.d.L.)
* Correspondence: mkrahmer@inti.gob.ar (D.M.K.); antonio.egea@upc.edu (A.J.S.E.); Tel.: +54-011-4754-4072 (D.M.K.); +34-934-054-024 (A.J.S.E.)

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Abstract: Free-cutting steels are developed to produce large quantities of parts with low mechanical behavior, mainly for automotive sector. These alloys contain phosphorous, lead, sulfur, and manganese that help to improve the machinability and surface roughness. However, due to the toxicity of lead, steel mills in recent years have been focusing on non-toxic steels to produce minimum environmental pollution and better machinability. The present work investigates the tool wear during dry and wet turning of free-cutting steels (SAE 1212, SAE 12L14, and SAE 1215) by using uncoated hard metal inserts at three cutting speeds. Additionally, a EDS analysis was performed to determine the presence of Mn and S elements at the rake face of the cutting tool that can induce a higher adhesion of manganese sulfide (MnS). The results show that the SAE 12L14 steel has the best performance in terms of tool life at different cutting speeds. This difference is maximum at the lowest cutting speed, which gradually decreases with the increase of the cutting speed. The wear behavior is evaluated in the three steel alloys at each cutting speed and, consequently, the tool wear exhibits a slightly better performance in the dry machining condition for higher cutting speeds (180 and 240 m/min), independent of the steel alloy. Finally, EDS analysis confirms the presence of Mn and S elements at the rake face of the inserts machined in dry condition. Hence, MnS is expected to interpose between the machined surface and cutting tool surface to behave similar to tribofilm by reducing the wear on the cutting edge.

Keywords: free-cutting steel; wear; dry turning; wet turning; uncoated carbide; adhesion layer

1. Introduction

The steel mills are developing some grades of steel called free-cutting steels (FCS) to reduce the use of cutting fluids during the cutting processes. It is well known that the use of cutting fluids in machining was initiated by Taylor in 1894 [1], who used water in the turning of steel to increase the cutting speed by 33%. However, the high oxidation nature of water and its lack of lubrication capacity could damage the cutting tool and increase the tool's wear [2]. In recent years, other important aspects were also considered, such as health care of operators, environment, and the cost of liquids, which is between 7.5% and 17% of the cost of a machining part [3]. The present trend is to use alternative techniques, such as dry machining [4], electrocutting [5], cryogenic [6], cold compressed air [7], or minimum quantity of lubricant (MQL) [8], with the aim to reduce environmental impacts.

The machining processes are analyzed by considering the influential factors, such as the type of cutting processes, materials to be machined, and the material of the tool [9]. The selection of these factors would provide basic information for selecting the suitable cutting fluid [10]. Despite the fact, there are circumstances in which the best solution is obtained by using lubricant in particular conditions. For example, the materials with low thermal conductivity, such as titanium and nickel alloys require a system called "high-pressure coolant" (HPC) [11]. Their proper application in the cutting area helps to reduce the temperature on the cutting edge of tool [12], thus, increasing the tool life [13]. The results indicated that several parameters, such as cutting speed, chip breakage and thrust forces play a key role in improving the quality of machined surface [14]. Isik et al. [15] investigated the effect of cutting fluids during turning of steel SAE 1050 by using ISO P25 carbide tool and obtained a substantial reduction in tool wear under the wet machining. Priarone et al. [16] studied that the machinability of Ti-48Al-2Cr-2Nb alloy in terms of tool life is advantageous for emulsion mist, as compared to MQL and dry cutting. On the other hand, Gill et al. [17] analyzed the behavior of cryogenically treated tungsten carbide inserts utilized in dry and wet orthogonal turning. They found that these inserts performed significantly better under wet conditions for continuous as well as interrupted machining modes, especially at higher cutting speed. Jomaa et al. [18] compared the machinability and surface integrity of three mold steels during dry and wet machining. They observed that hardened mold steels can perform better in terms of tool wear and surface finish in dry machining, depending on the cutting speed. Ibrahim et al. [19] introduced the performance of ultrasonic-assisted turning of aluminum 6061-T6, which showed significant improvements in surface roughness and tool wear during wet machining. Moreover, Patrick et al. [20] performed turning under dry conditions and also used three coolants, such as oil, water, and palm oil at spindle speed of 355 rpm. They concluded that water as a cutting fluid reduced the heat generation, increased hardness of workpiece material, and produced the finest grain structure. Feed rates also have significant effects on surface roughness when groundnut oil based cutting fluid was used in turning of AISI 1330 alloy steel with a high-speed steel tool [21]. Kuram et al. [22] reported that the use of vegetable cutting oils reduced the thrust force and improved surface roughness at different spindle speeds and feed rates during drilling of AISI 304 stainless steel. Furthermore, the results indicated that an increase in spindle speed decreased the thrust force and surface roughness, while an increase in feed rate increased the thrust force, and hence the surface roughness.

In free-cutting steels, Luiz and Machado [23] explained in details according to the technological trends to improve their machinability and promote the replacement of lead to avoid toxicity. Thus, steel mills have developed new grades of free-cutting steels by adding sulphur, bismuth, calcium, selenium, and also zirconium to control the size and shape of manganese sulphides. They also referred MnS as microstructural compound, which helped in chip breakage and reduced the tool wear. Almeida et al. [24] studied the effect of machinability for AISI 12L14 with three residual elements (Cr, Ni, Cu) and found that these elements significantly influence its machinability but the lowest residual levels are not always good. On the other hand, Lane and his co-workers [25] tested the wear of polycrystalline diamond inserts (PCD) on alloys of aluminum AA6061 and steel AISI 1215. Additionally, examined that both the forces and wear rate were significantly higher during machining of steel AISI 1215. Furthermore, Leeba Varghese et al. [26] studied the influence of machining parameters on material removal rate and surface roughness during the dry turning of 11SMn30 free-cutting steel. Finally, Xu and coworkers investigated the cutting force and wear mechanism during high-speed turning of AISI 12L14 with Chemical Vapor Deposition (CVD) coated carbide tool GC4205 [27]. Later, they also studied wear mechanism by using Finite Element Method and experimental methods on high-speed turning of AISI 1215 steel with uncoated and multilayer carbide tools [28]. Following this last research topic, the present work is to investigate the importance of the cutting capabilities of free-cutting steels (FCS) during dry and wet machining. For this, three grades of carbon steel (SAE 12L14, SAE 1215, and SAE 1212) have been studied by using uncoated hard metal inserts and three commonly used cutting speeds: 150, 180, and 240 m/min. The wear evolution of the cutting tool is investigated experimentally to analyze the differences in wear rates for different FCS, machining conditions, and cutting speeds. In this end, the novelty of this work is to analyze the auto-lubrication characteristics in dry machining, which showed better cutting capabilities due to the adhesion of MnS, compared with the same machining configurations by using lubricant. These technological findings are interesting for industries with the aim to reduce the use of lubricants, which are associated with economic and environmental hazards.

2. Methodology

Three different grades of FSC, SAE 12L14, SAE 1215, and SAE 1212, have been studied in this work. The materials used in the turning experiments were drawn bars of 38.1 mm in diameter and 350 mm in length. Table 1 shows the chemical composition (% by weight) and Brinell HB hardness that were measured with optical emission spectroscopy (model: M8 spectrolab, Spectro, Kleve Germany) and Instron Wolpert durometer (model: S8-233971, Instron, Norwood, MA, USA) in our facilities. These three steels present similar chemical composition, except SAE 12L14 that contains lead.

Table 1. Chemical composition (wt%) and material hardness (HB) of the three free-cutting steels (FCS).

Material	C	Mn	S	P	Pb	Fe	HB
SAE 12L14	0.074	1.065	0.313	0.055	0.246	Balance	161
SAE 1215	0.065	1.000	0.318	0.052	-	Balance	155
SAE 1212	0.070	1.050	0.303	0.055	-	Balance	161

The metallographic analysis of the steel SAE 12L14 showed that it has a hot-rolled microstructure, constituted by a matrix of equiaxed grains of ferrite. A lower proportion of perlite was uniformly distributed in bands and heterogeneously in the matrix, which corresponded to a grain size equivalent to N° 6 $\frac{1}{2}$ (ASTM E112 [29]), as shown in Figure 1a. Figure 1b shows the inclusions that correspond to type A (sulphides) with the grain series of N° 2 $\frac{1}{2}$ and N° 2, while the type D (oxides) are represented by finer grain series of N° $\frac{1}{2}$. The microstructure of the surface and core presented a similar grain size, where plastically deformed grains were observed due to the cold working operation (drawing). A numerical control lathe Promecor SMT 19 (Promecor, Córdoba, Argentina) was used to perform experimental tests. Cutting tools with uncoated inserts (type CNMG120408 and quality ISO P40, Kennametal, Latrobe, PA, USA) and specific tool-holder (type MCLNR-2525M12, Kennametal, Latrobe, PA, USA) were used during the experiments. The CNMG insert on tool-holder presents a rake angle of −4°, which is a common configuration for low and medium-carbon steels. The geometrical parameters and chemical composition of the uncoated insert are shown in Table 2. The insert had a clearance angle of $\alpha = 5°$, rake angle of $\gamma = -4°$, and inclination angle of $\lambda = -5°$.

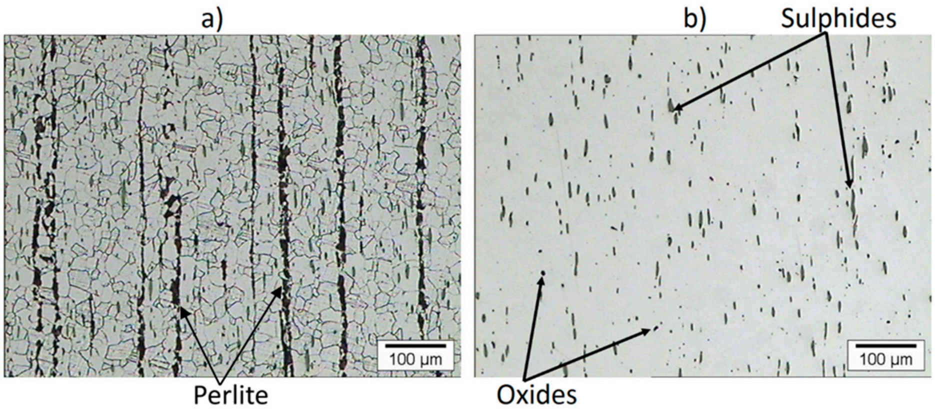


Figure 1. Material's microstructure of equiaxed grains and perlite distributed in bands (**a**) and inclusions of sulphides (grey dots) and oxides (black dots) (**b**) of the SAE 12L14.

The cutting parameters are listed in Table 3. Firstly, the preliminary tests were performed to estimate constant material removal rate with a constant depth of cut of 1.25 mm. Regarding the cutting speeds, the references were taken from the leading manufacturers of carbide inserts in a range of 150 to 240 m/min. The bars of 38.1 mm diameter and length of 350 mm were fixed between the spindle and the tailstock. The wear (VB) evolution at the cutting edge of the inserts was determined by using a Dormer optical measuring benchmark. Despite that, the standard ISO 3685 [30] established a criterion of interruption test of VB = 0.3 mm. Here, the wear stop criterion was set at the value of VB = 0.5 mm for these FCS due to the fast wear rate found during the experiments.

Table 2. Geometrical and chemical composition of the cutting tool used for the experiments.

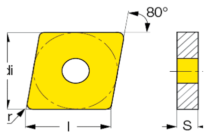
Code	Geometrical Description	Sizes (mm)			Chemical Composition (wt%)			
		s	r	l	C	Ti	Co	W
CNMG 120408ISO P40		4.76	0.8	12	16.60	3.85	12.10	60.80

Table 3. Cutting parameters and the stop criteria of the wear test.

Cutting Speed *Vc* (m/min)	Feed Rate *a* (mm/v)	Depth of Cut *p* (mm)	Type of Lubricant	Flow (L/min)	VB (mm)
150; 180; 240	0.125	1.25	None	-	0.5
			5% of emulsifier	10	

Finally, the morphology of the wear areas was determined with a scanning electron microscope (FEI model: QUANTA 250 FEG, FEI, Eindhoven, The Netherlands). Furthermore, another microscope (Philips SEM 505, Philips, Eindhoven, The Netherlands) with a EDS module (UTW-Sapphire, model: PV7760/79 ME, Ametek, Eindhoven, The Netherlands) was utilized to determine the chemical compositions of the lubricated areas. Figure 2 shows the machining and measurement techniques used in the wear tests. Finally, the surface integrity was also often analyzed to determine the level of damage of the cutting tool with an optical surface profiler (Alicona, InfiniteFocus, Alicona, Graz, Austria). All the experiments were carried out in the laboratory of INTI-Mecánica (Argentina).

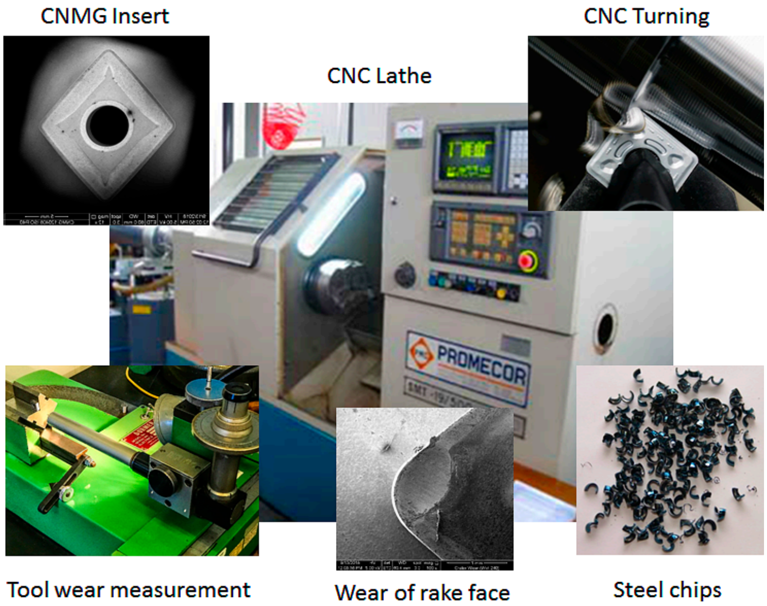
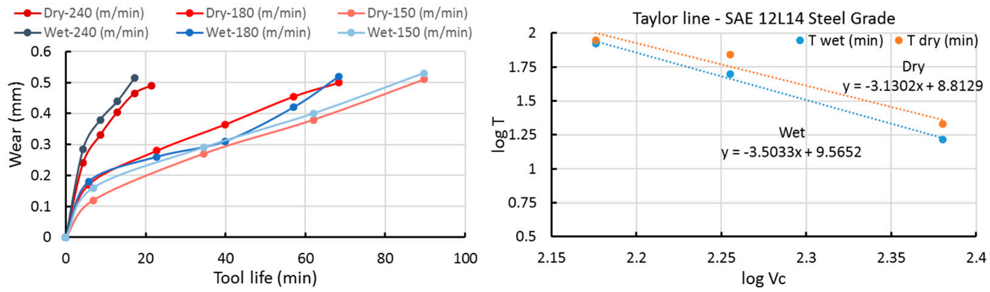


Figure 2. Schematic of the machine and tools to perform the cutting tool wear experiments.

3. Results and Discussion

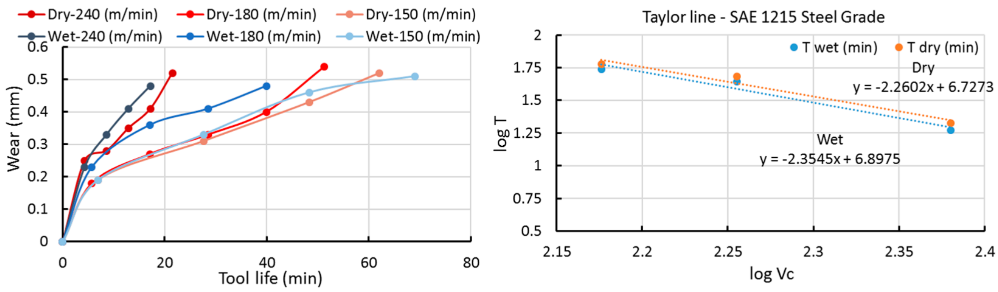
The wear and the corresponding Taylor curves were determined for each of the three cutting speeds. The results exhibited the wear evolution of dry and wet machining tests for each steel. The second degree polynomial adjustment curves were used (R^2 minimum = 0.958) to obtain the useful tool life for VB = 0.5 mm in each case. For each metal grade, 20 bars of 1.5 m length were machined. Subsequently, a total of 0.8 T and 307 m of material was machined during the experiment.

From the analysis of Figures 3a, 4a and 5a, it is clear that for higher cutting speed the value of VB = 0.5 mm is reached in less time, and subsequently, a fast wear evolution on the cutting tool is observed. In all steel grades, the cutting tool took more time to reach a wear evolution of VB = 0.5 mm during dry machining. This means that dry machining condition presented a lower wear evolution slope than that obtained for wet machining, which may be due to the formation of a solid tribofilm at the interfaces [31]. However, independent of the steel alloy the wear difference between the dry and wet conditions increases for higher cutting speeds (240 or 180 m/min). In particular, dry machining exhibits a better tool life at higher cutting speeds than the wet machining condition. Regarding the Taylor curves (Figures 3b, 4b and 5b), it is shown that the wear trend of the insert depends on the speed and tool life evolution for both machining conditions. SAE 12L14 exhibited the best wear performance compared with the other two steel grades, particularly at low cutting speed and dry conditions. Accordingly, Jomaa et al. [18] also studied the wear evolution during dry and wet machining in three steel grades. They found lower wear rates and better surface properties in dry machining, mainly attributed to the material adhesion and the chemical composition of the steels. Finally, in order to establish the possible causes by which the inserts reached the criteria of VB = 0.5 mm in less time during wet condition, the EDS analysis was performed on the rake face of the inserts for SAE 12L14 carbon steel during wet and dry conditions. Figure 6a shows the average weights in percentage of sulphur (S) and manganese (Mn) on rake face in dry and wet conditions at different cutting speeds in SAE 1212 and SAE 12L14 (SAE 1212 was selected as its behavior was very similar to SAE 1215). The margin errors represent the measurement deviation of ten measurements. Figure 6b exhibits the electronic microscope images of two cutting tools with the tool tip degradation and the adhesion of MnS along the tool edge.



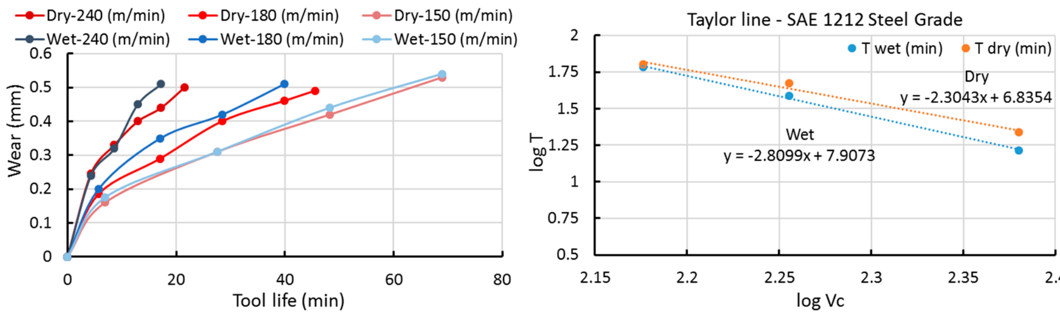
(**a**) (**b**)

Figure 3. Wear curves for dry and wet conditions at the three cutting speeds (**a**) and Taylor curves (**b**) for SAE 12L14 carbon steel.



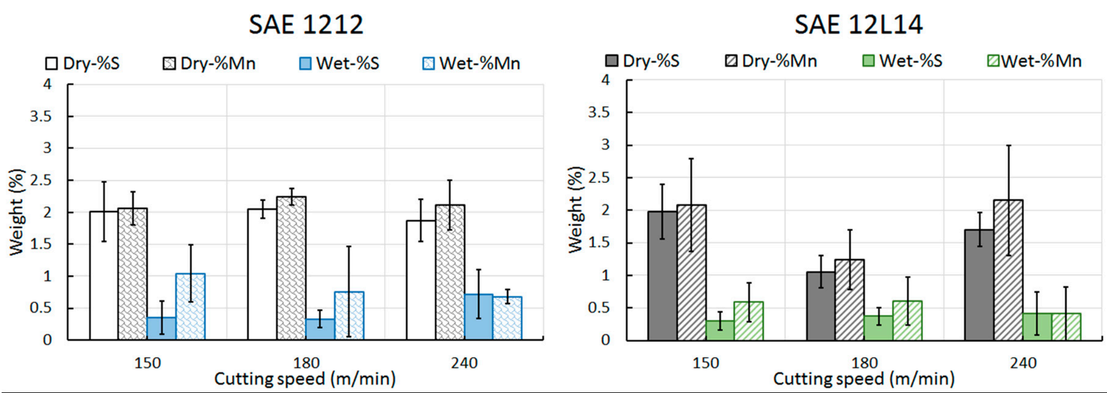
(**a**) (**b**)

Figure 4. Wear curves for dry and wet conditions at the three cutting speeds (**a**) and Taylor curves (**b**) for SAE 1215 carbon steel.



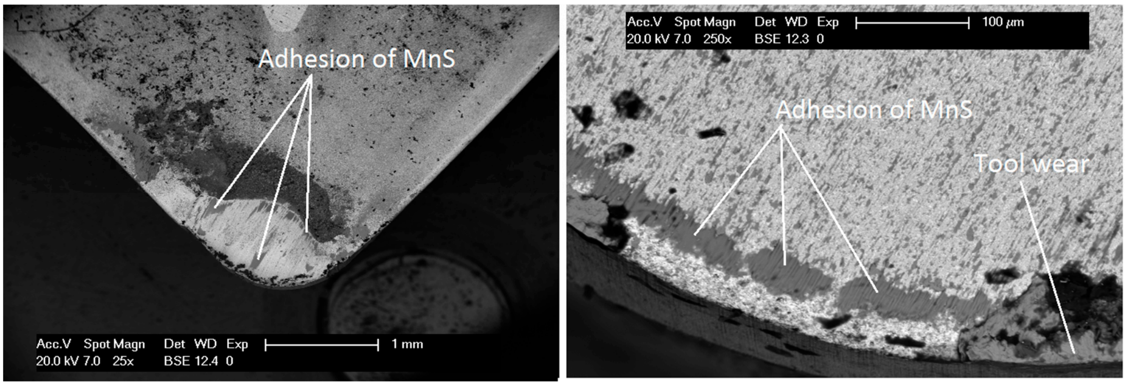
(**a**) (**b**)

Figure 5. Wear curves for dry and wet conditions at the three cutting speeds (**a**) and Taylor curves (**b**) for SAE 1212 carbon steel.



(**a**)

Figure 6. *Cont.*



(**b**)

Figure 6. (**a**) Average percentage of weight of S and Mn at the rake face for dry and wet machining conditions at different cutting speeds. (**b**) Microscope images of the rake face with the tool wear and the adhesion of MnS.

The results obtained from EDS showed that S and Mn elements were found in a higher percentage in the rake face of the cutting tool. The high percentage of Mn and S could be due to material adhesion at the rake face in the form of Manganese Sulfide (MnS), as discussed by Xu et al. [27]. They also described that MnS lubricant zone formed on the chip–tool contact area, which improved the wear resistance of the cutting tool [28]. Therefore, the MnS behaved similar to a tribofilm at the tool and workpiece interfaces, consequently, attenuating the wear progression in the cutting tool. In the present study, it is seen that both the percentages of S and Mn were significantly higher in inserts during cutting in dry condition compared to wet condition. This fact could explain why the wear of tool inserts is less in dry condition than the wet condition. In addition, there could be a negative interaction between the cutting fluid and the adhesion of the MnS on the tool. In this way, the amount of compound that adheres on the rake face depends on machining (dry or wet) and the cutting speed.

Figure 7 shows the insert topography with adhesion and different wear progression. This measurement was done with a high-resolution scanner (Alicona, InfiniteFocus). The protective and auto-lubrication layer of MnS was observed on the rake face of the tool tip. After several meters of machining is onset of the wear of the tool tip, as shown in the Figure 7b. At the end of a test, a prominent tool wear and micro-crack is denoted in the tool tip, combined with material adhesion, which is also found on the rake face. This layer of MnS can retarded the tool wear and increased the process stability, in particular when using dry machining conditions.

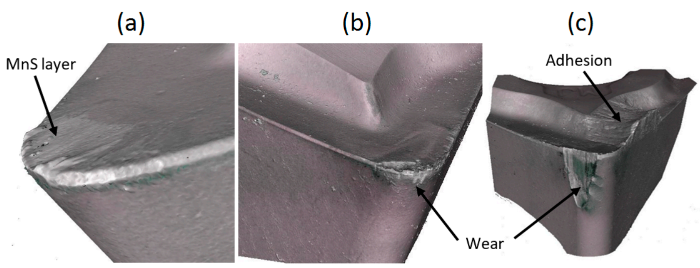


Figure 7. Characteristics found on the rake fake of the cutting tool: (**a**) adhesion on rake face; (**b**) initiation of the wear after 20 min of tool life with a velocity of 180 m/min and dry conditions; (**c**) adhesion and prominent wear of the insert when reaching the stop criteria.

From the results, it is clear that the lubricating effect of the cutting fluid was negligible compared to that provided by the adhesion of MnS. On the other hand, the cooling effect seems to be less for the inserts with a speed range used in the present study. Finally, Figure 8 shows the Taylor curves corresponding to SAE 12L14 and SAE 1212 machined with different conditions and cutting speeds.

This graph will provide additional information (SAE 1212 was selected as its behavior was very similar to SAE 1215). Previous authors have addressed that the adhesion of MnS layer promoted a tool wear reduction, although most of them did not quantify different cutting parameters combined with machining conditions (with and without lubricants) for several common steel grades. In particular, Luiz and Machado [23] focused their work on the reduction of environmental impact and health care in turning operations. They proposed to reduce the use of cutting fluids and replace the free-cutting steels with lead, given the toxicity of the latter. Our work shows that the free-cutting steels can be used in machining without using cutting fluids as they produced a higher wear rate on uncoated hard metal inserts. Moreover, without lead, free-cutting steels have a similar behavior to the alloys with lead during machining. Additionally, Xu et al. [27] performed experiments with multilayer inserts by CVD in turning of SAE 12L14 steel by using cutting fluid at a speed of 500 m/min. They found that under these conditions a lubricant zone was formed by MnS, which decreased the wear rate. Whereas, the same authors [28] performed experiments with multilayer inserts coated by CVD and uncoated inserts during turning of non-toxic steel SAE 1215 in dry machining at a cutting speed of 500 m/min. They examined that as compared to uncoated inserts, a lubricant zone was formed by MnS in the coated inserts. Our work is complementary to the aforementioned cases. We have estimated the adhesion of MnS at the rake face in uncoated inserts at lower cutting speeds. This compound has shown an auto-lubrication characteristic in these steels with better performance than a conventional lubricant.

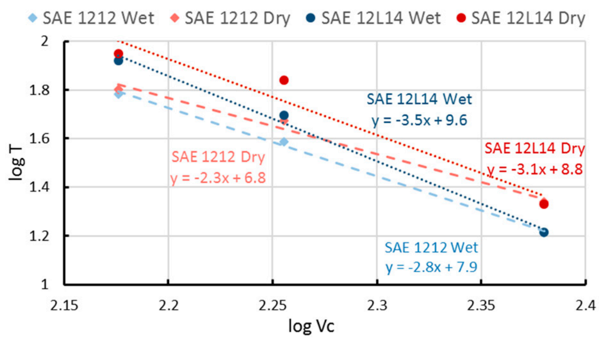


Figure 8. Taylor curves for the uncoated cutting tools tested in SAE 12L14 and SAE 1212 carbon steels.

Regarding the aforementioned results, the present work described that SAE 12L14 was more sensitive in changes with cutting speed, as shown in the slope of the Taylor curve, while SAE 1212 and SAE 1215 presented a similar trend. Since the slope depends on the material of the tool and the material to be machined, this significant difference could be attributed to the lead that constituted SAE 12L14. Although, SAE 12L14 exhibited better anti-wear capabilities with respect to SAE 1212 and SAE 1215, but the differences were diminished with the increase of the cutting speed. For productivity reasons the metal cutting industry commonly uses the highest cutting speeds depending on the cutting tool, workpiece material, and machining operation. Consequently, the present work proved that unleaded FCS are excellent substitutes of SAE 12L14 when machining with uncoated carbide cutting tools.

4. Conclusions

The present paper evaluated the machining capabilities and the wear evolution of the cutting tool during a turning operation of three free-cutting steels, under dry and wet conditions, and at three different cutting speeds. The following conclusions can be withdrawn:

1. The tool wear evolution was attenuated in dry machining with respect to wet machining independent of the steel alloy, and in particular, for higher cutting speeds (240 and 180 m/min). The main reason of the wear reduction was attributed to a higher adhesion of MnS found at the rake face of the cutting tool during the dry machining, as denoted in the EDS analysis. This MnS generated a protection layer between the surface of tool and machined surface, which decreased the friction and ultimately, reduced the wear on the cutting edge.

2. In three free-cutting steels, the SAE 12L14 carbon steel, presented the best performance in terms of tool life for the lower cutting speeds, but no noticeable differences were found for cutting speed of 240 m/min. Additionally, the wear at the rake face of the cutting tool was lower at lower cutting speed and increased with the increase of the cutting speed at all machining condition of steel alloys.
3. The Taylor curves showed that SAE 12L14 was more sensitive to the cutting speed and type of machining condition. This difference can be noted to the lead, which enhanced the material's machinability and, consequently, affected the slope of these curves that were associated to the material of the cutting tool and the workpiece to be machined.
4. Auto-lubrication characteristics of these steel grades have shown a better machining capabilities compare to the lubricated conditions. Consequently, lubrication did not bring any benefit for the studied machining conditions and materials; instead, it is showed economic and environmental disadvantages. Therefore, the lubrication should be considered for more challenging machining solicitations (high-speed machining) or hard-to-cut materials.

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