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Review

A Review of the Factors Influencing Surface Roughness in Machining and Their Impact on Sustainability

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Abstract: Understanding surface roughness generation in machining is critical to estimate the final quality of the part, optimize cutting conditions, reduce costs and improve manufacturing sustainability in industry. This work presents a review of the factors that affect surface roughness generation in machining (turning/milling) processes. Up to twenty-five different factors were identified, which were classified as setup factors (cutting tool, machine tool/fixturing and workpiece factors), operational factors (cutting and process parameters) and processing factors, which are related to the resulting cutting processes, such as built-up edge, chatter or tool wear. The importance of understanding these factors to improve machining sustainability is highlighted through three case studies, ranging from a simple change in the cutting insert to a more complex case where a controlled surface roughness leads to the elimination of a grinding stage. A case study illustrating the potential benefit of MQL in the sustainability of the machining process is also reported from the mold manufacturing industry. In all of the cases, the improvement in sustainability in terms of the reduction in kg of CO_2 equivalent is notable, especially when grinding operations are reduced or eliminated from the manufacturing process. This paper can be of interest to practitioners in finishing operations at milling and turning operations that want to increase machining sustainability through a deep understanding of surface roughness generation.

Keywords: surface roughness; machining; sustainability

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1. Introduction

Surface roughness is one of the most important characteristics of product quality which has a direct impact on product performance, aesthetic appearance, fatigue, corrosion resistance, etc. This important product specification is defined in technical drawings by surface roughness annotations, such as Ra (arithmetic mean height), Rt (total height) or Rq (root mean square height) [1]. These requirements are considered by process planners in order to select the correct machine tool equipment, cutting tools or cutting parameters, and these decisions have a clear impact on machining sustainability [2]. Very often, process planners directly deal with cutting parameters, such as the cutting speed, feed rate and depth of cut, to ensure surface roughness specification. However, it is well known that surface roughness is not influenced by these cutting parameters alone, and many other factors have been identified and studied, such as the wear of the cutting tool, workpiece and cutting tool material; the geometry of the cutting tool; the stability and rigidity of the machine tool/fixturing system; the emergence of a built-up edge during cutting; the use of a refrigerant/cutting lubricant; and so on [3]. Research reviews related to factors that affect surface roughness are reported in [4,5], and relevant books, such as those presented in references [3,6,7], that are related to machining and cutting theory give a general overview of the complexity of surface roughness generation and the large number of factors that are interrelated.

Although the relationship between surface roughness and many different factors in the machining process has been shown in the literature, the influence of surface roughness on machining sustainability is commonly overlooked. In fact, when dealing with machining sustainability, most of the available research works are related to the use of dry or near-dry cooling techniques [8–10] and cutting parameter optimization [9,11,12], since these two strategies are the most effective. On one hand, different cooling/lubricating systems can be applied in machining, such as flood, air, minimum quantity lubrication (MQL), cryogenic cooling, hybrid cooling (cryogenic and MQL) and high-pressure jet-assisted machining (HPJAM) systems [13–17]. Near-dry cooling techniques can increase tool life, improve surface roughness and remove flood cooling systems, which are well known to be harmful to health operators and the environment. Dry machining is the best option for machining sustainability in relation with cooling/lubricating systems, but it is only considered acceptable by manufacturers when it ensures at least equal product quality and material removal rate as those obtained in wet machining [18]. Currently, dry machining is still challenging in terms of cutting tool life and workpiece quality, except for some specific applications, such as machining cast iron [19]. On the other hand, for a given machining scenario where only the cutting parameters may be modified, their optimization may provide an important improvement in terms of quality, tool life and productivity, and thus, in sustainability [11].

Apart from these sustainability strategies, other works are more focused on the energy consumption of machine tool components (e.g., hydraulic units, lightening and basic module run) and their cutting and idle/steady state. Under this approach, different strategies, such as the implementation of lightweight components [20], the adjustment of motors to the machine cycle requirements or switch-off and the reduction in warm-up tactics [21], have been studied to reduce cost and energy consumption and increase sustainability without compromising their functionality, usability, productivity, accuracy, etc. [22], and some of them have been recently reviewed [23,24].

The literature presents extensive work in machining, surface roughness and sustainability according to a detailed search in reputable databases (Web of Science Core Collection): during 2023, 93 papers were published in comparison to 76 (2022), 61 (2021) and 58 (2020) papers in previous years, which provides a groundwork for a fundamental study on how surface generation influences sustainability outputs. The research trend states that there is a growing interest in exploring lubrication strategies with nanofluid or nanoparticle-assisted minimum quantity lubrication [25–28] and vegetable oil-based fluid [29] or mitigating carbon footprint while improving surface characteristics, among other eco-friendly green approaches [30]. Other trends include integrating cutting-edge preparations in cutting tool development [31] using different combinations of substrate and coating materials [32], and incorporating ultrasonic vibration into machining strategies [33], among others. Nevertheless, if one is focused on finishing operations in milling and turning operations, there exist many decision variables that can improve sustainability. Simple aspects, such as the proper type of tool in terms of geometry and material, can lead to higher productivity within admissible surface roughness values, improving sustainability by reducing costs and energy consumption. As a result, it is clearly shown that a correct understanding of all factors that are related to surface roughness generation is of great importance to apply more effective and sustainable machining practices.

This work presents a review of the factors that affect surface roughness generation in machining (turning/milling) processes and the main research works where those factors are analyzed. The factors are classified in three categories and five subcategories in order to facilitate the identification of the factors and their relationship since, due to the complexity of surface roughness generation, some factors have a more direct influence than others. The three identified categories are setup factors (cutting tool, machine tool/fixturing and workpiece factors), operational factors (cutting and process parameters) and processing factors (built-up edge, chatter, tool wear, etc.). To illustrate the importance of understanding surface roughness generation to improve machining sustainability, three case studies are shown. As presented in the case studies, correct decisions in insert geometry selection, cooling systems or tool replacement and cutting parameter selection may provide a high reduction in kg of CO_2 equivalent. The research work presented may be of interest to practitioners in the machining industry who want to improve machining sustainability in conventional processes. Note that this research work is limited to finishing operations in conventional machining processes, such as milling and turning processes.

This paper is organized as follows: Section 2 shows the proposed classification of the factors that influence surface roughness. Section 3 reviews the effects of the identified factors according to the relevant research conducted in the literature, providing relevant information and graphical data about experimental relations among surface roughness and different factors. Section 4 presents three case studies to illustrate the potential improvement in machining sustainability by properly working on some of the factors identified. Finally, Section 5 concludes the paper.

2. Classification of Factors

According to the literature review, the factors that influence surface roughness generation may be classified into three main categories: setup factors, operational factors, and processing factors.

Setup factors refer to the factors defined at the process-planning level. These factors may have a very important impact on surface roughness, and they are kept constant during machining; thus, only the interaction of these factors with the generation of different cutting phenomena may produce different roughness values during production. Three subcategories may be identified within the setup factors: cutting tool, machine tool/fixturing and workpiece factors.

Operation factors refer to the parameters at the machine tool level that can be modified on the spot by either changing the settings or the NC program on the machine tool. These factors are divided into two subcategories: cutting parameters and process parameters. Cutting parameters include parameters such as the cutting speed, feed rate or depth of cut, and process parameters are related to the coolant, cutting strategies and so on.

Processing factors refer to the factors related to specific cutting phenomena that influence the surface roughness generation. When they appear, these factors have a clear contribution to the final surface roughness. These factors are tool wear, vibrations/chatter, built-up edge, plastic side flow and back cutting.

It should be noted that this classification facilitates the understanding of surface roughness generation in terms of independent and dependent variables. Setup and operational factors are independent, and they are defined according to the process planner and/or machining operators. However, processing factors are dependent on both setup and operational factors. For instance, vibrations as a processing factor will impact the surface roughness, but the importance of vibrations as a processing factor will depend on previous factors such as the geometry of the insert, dynamics of machine tool/workpiece/fixturing, cutting parameters, etc., and it will also depend on other processing factors such as tool wear or built-up edge. Figure 1 illustrates this classification and shows the relationships between them. The explanation of each factor and its impact on surface roughness is detailed in the next section.

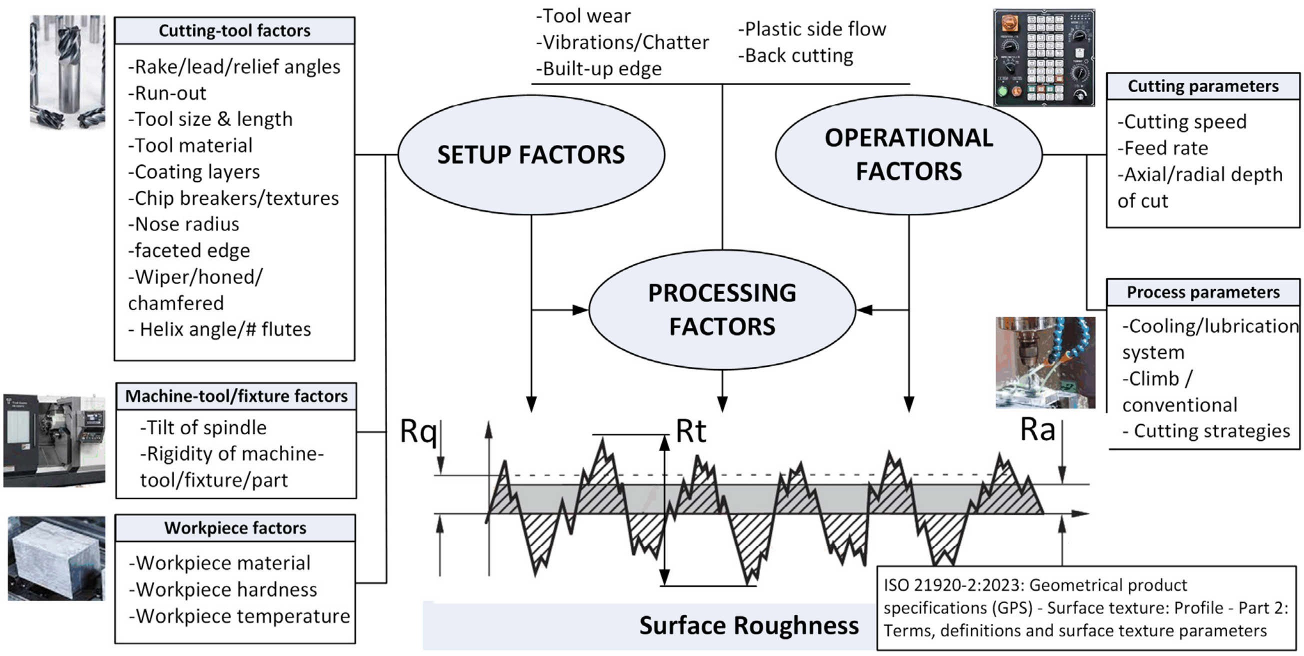


Figure 1. Factors that influence surface roughness generation.

3. Review of Factors Related to Surface Roughness

3.1. Setup Factors

3.1.1. Cutting Tool Factors

Cutting tool factors are the most important ones at the planning stage that contribute to surface roughness generation. Within cutting tool factors, three subgroups can be identified: tool geometry, insert geometry and insert material.

- Tool geometry
    - Rake angle: In general, the use of positive rake angles in machining tends to reduce the cutting pressure, which avoids problems related to workpiece/cutting tool deflection and vibrations. It also prevents adhesion by reducing the built-up edge phenomenon, and thus, positive rake angles tend to produce a better surface roughness [34]. On the contrary, negative rake angles increase the cutting-edge strength but increase cutting forces and make it easy for the workpiece material to adhere to the cutting tool, increasing the surface roughness [7]. For instance, Adesta et al. [35] reported a trend of higher roughness values when increasing the negative value of rake angles when turning medium-carbon steel with cermet tools (Figure 2a).
    - Lead angle: When a larger lead angle (smaller entering angle) is applied, the load is spread over a greater length of the edge, creating a smoother cutting action. Since the load is reduced, cutting with larger lead angles can help reduce vibration possibilities, improving the surface roughness [34]. Furthermore, lead angles define the axial and radial components of cutting tools, which will impact tool/workpiece deflections [34].
    - Relief angle: The relief angle provides a gap between the insert and the workpiece to avoid rubbing after shearing the material and makes the cutting edge move along the workpiece easily [36]. The relief angle mainly influences the tool wear rate, which will indirectly influence the surface roughness. In general, it is considered that the surface roughness increases as the relief angle becomes close to 0°. Figure 2b shows the influence and evolution of flank wear according to the relief angle when turning AISI 4340 alloy steel in [36] after a cutting time of 20 min, which may have a subsequent impact on the surface roughness. In a recent work, Knápek et al. [37] also showed the influence of the

relief angle on the surface roughness and delamination in machining carbon fiber composite boards. Smaller relief angles produce higher wear rates that generate delamination and higher surface roughness values.

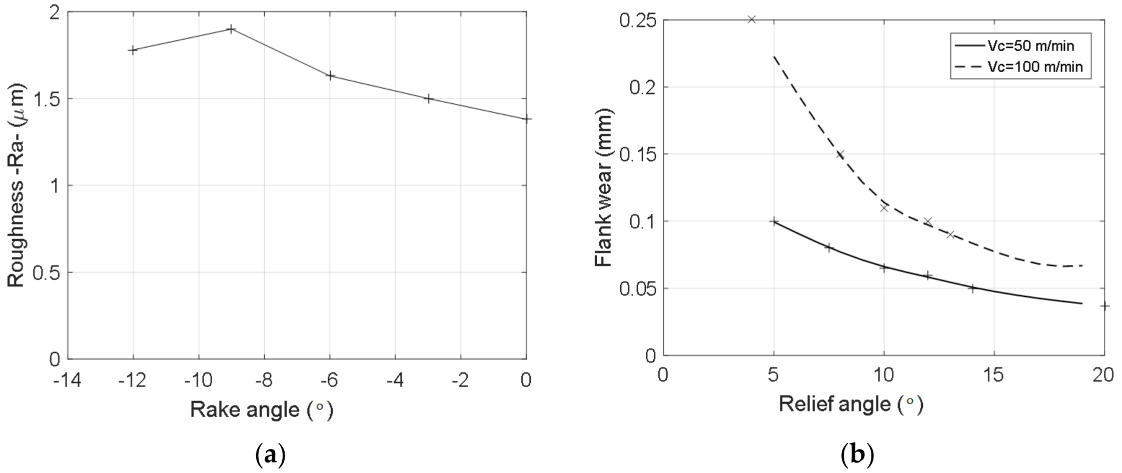


Figure 2. (**a**) Evolution of surface roughness as a function of rake angle in turning medium-carbon steel with cermet. Values marked as + extracted from [35]. (**b**) Influence of relief angle on flank wear impact after 20 min of machining time in turning AISI 4340 alloy steel. Values marked as + and × extracted from [36].

- Tool overhang: Tool overhang is directly related to vibrations that negatively impact surface roughness. Chang and Lu [38] showed that the average roughness at both the feeding and axial directions increases due to the increase in the overhang length due to the reduction in the rigidity of the tool. Some authors have studied how to locate the optimum range of tool overhang to minimize tool vibrations [39] and studied the dependence of tool overhang on both surface roughness and tool wear [40].
- Radial and axial run-out: One of the main factors that affects the surface finish in milling operations is the deviation in the location of the cutting tool teeth, especially in indexable cutting tools (Figure 3). The run-out refers to small deviations in the relative positions of the different inserts or cutting tool teeth that compose the tool, mainly due to the manufacturing tolerances or inaccurate assembly in the cutting body when inserts are replaced [41]. Baek et al. [42] showed the influence of run-out in milling operations in AISI 1041 steels and presented a surface roughness model considering the run-out effect to optimize the feed rate to obtain a maximum material removal rate. Krüger and Denkena [43] defined the relationships between cutting forces for a given run-out tool and the surface roughness generated in end mill operations. They presented and experimentally validated a model-based approach to identify the actual tool run-out and surface roughness from measuring cutting forces. Schmitz et al. [44] presented a model to explain the relationship between surface roughness generation and run-out in 6061-T6 aluminum alloys. The authors showed that, due to the presence of run-out, new regions of instability related to chatter occur if the harmonics of the run-out frequency reach the dominant natural frequency of the system.
- Helix angle and flutes: In end milling operations, the helix angle and flute number may have significant impacts on the surface roughness. Sur et al. [45] compared the performance in the peripheral milling of Ti-6Al-4V alloys with fixed and variable helix tools and showed that large helix angles performed best. Chen et al. [46] studied the effect of different tool helix angles in tilt side milling of Al 6061 thin-walled plates. Their experimental results showed that the helix angle had a high impact on the surface roughness, varying from 1–2 μm for a 10° helix angle to less

than 1 µm for 40–50° helix angles. On the other hand, the number of flutes is also an important factor, since these channels in the tool allow the chips from the cutting zone to be removed. More flutes mean higher removal rates but less efficient chip evacuation, which may produce excessive heat or clogging that can affect the surface roughness. For instance, Danyan et al. [47] showed that end milling operations in Ti-6Al-4V with three flute tools performed slightly better in terms of the surface roughness than four flute tools. Similarly, Çelik et al. [48] showed that when end milling of glass fiber reinforced plastic composites with cemented carbide tools, the use of two flutes resulted in a reduction of 50% in surface roughness with respect to the same tool with four flutes.

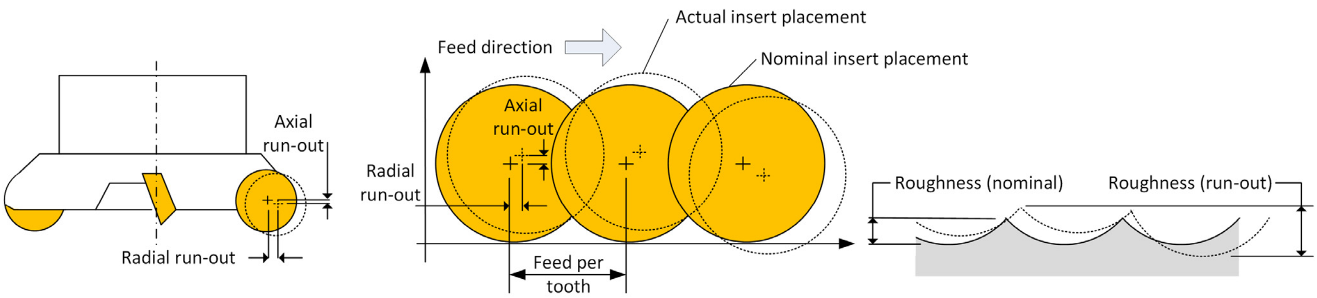
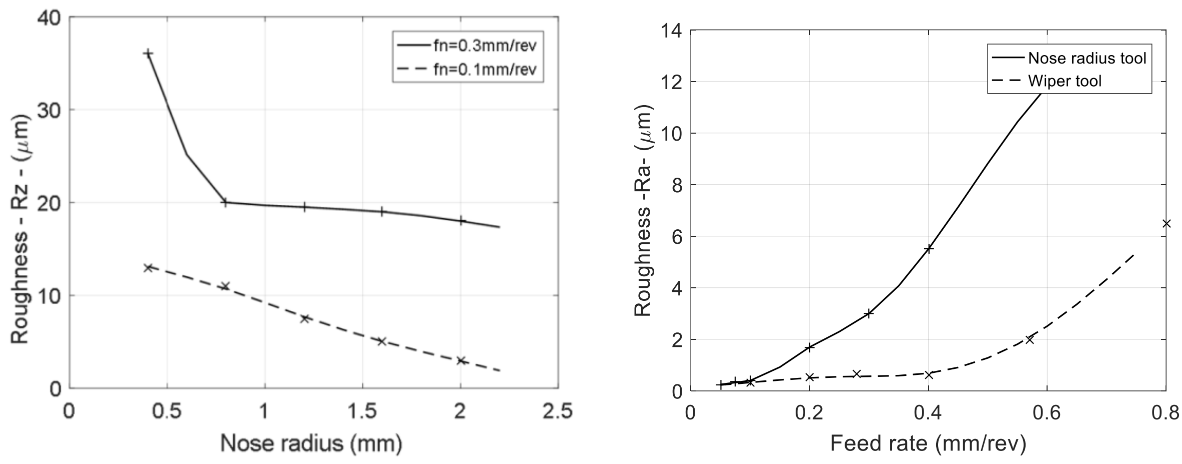


Figure 3. Run-out effect on surface roughness generation. Adapted from [41]. Reproduced with permission from Franco et al., International Journal of Machine Tools and Manufacture, published by Elsevier, 2004.

- Insert geometry:
    - Insert shape: The shape of the insert may be important since it is related to the vibration tendency during machining. Due to the small nose angle, rhombic or triangular designs may present less vibration tendency, which may improve surface generation. On the other hand, geometries with a large point angle, such as round or square inserts, present a stronger cutting edge, but they need more machine power, and thus, there is a higher tendency to vibrate, which may increase the surface roughness [34].
    - Corner configuration: The corner configuration heavily influences the strength of the cutting edge and surface finish. An insert with a nose radius is best in roughing applications where the surface finish is not critical. The radius encourages a longer tool life since heat from the machining operation dissipates across a greater surface area [34]. A big nose radius improves the surface roughness and cutting edge strength, but an excessively large radius may produce vibrations and chattering [36]. Shah et al. [49] experimentally showed that in turning operations of Ti-6Al-4V, tool nose variations ranging from 0.4 mm to 1.2 mm had a higher effect on the surface roughness that changed based on the feed rate or cutting speed. Deflection is also a primary concern limiting the size of the nose radius, since an increase in the nose radius increases radial cutting forces. In finishing operations, cutters with corner chamfered inserts or wiper inserts are commonly preferred. Chang and Fuh [50] studied different tool geometries under different side cutting edge angles, nose radii, side rake angles and chamfer angles in turning operations of pure aluminum and carbon steels. In the experimentation, the authors found that specific chamfered edge tools have the advantage of a limited chip contact length within the tool face, the cutting shear area, cutting forces and temperature decrease and it helps to reduce the built-up edge formation, improving the surface roughness. Wiper inserts can produce finer finishes than corner chamfer inserts at higher feed rates due to the special nose design with a long land. In fact, this geometry can reduce the surface roughness by a factor of two or more [51,52], and the degree

of improvement increases with the feed rate [3]. However, if large cutters are applied with several wiper inserts, the resulting finish depends significantly on the run-out errors of the cutter. Wipers are mainly used when short chips are produced, such as in machining cast iron or brass. In materials such as steel, chip flow may be difficult, which may produce large tangential and axial forces and, eventually, may generate chatter [3,34]. Figure 4 shows the effects of the nose radius and wiper tools on the surface roughness, adapted from [36,52].



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

Figure 4. (**a**) Influence of nose radius on surface roughness in turning AISI 4340 alloy steel. Values marked as + and × extracted from [36]. (**b**) Comparative assessment of surface roughness between conventional and wiper inserts in hard turning AISI 5140. Values marked as + and × extracted from [52]. Reproduced with permission from Grzesik and Wanat, International Journal of Machine Tools and Manufacture, published by Elsevier, 2006.

- Edge preparation: Unlike solid tools, where sharp edges are commonly found, indexable tools for both turning and milling operations may present different edge preparations such as hones (honed radius, waterfall and variable honed radius), chamfers and negative lands (similar to chamfered edges but with smaller angles), as well as combinations of these three [53] (Figure 5). It is well known that edge preparation has a significant influence on the tool life, surface finish and surface integrity of the machined part [54]. Chamfered edges and negative lands provide an effective negative angle to the cutting action to provide a stronger edge geometry, which makes the insert less prone to premature breakage. Increasing the edge preparation width increases the cutting resistance, but vibrations may occur, which may have a negative impact on the surface roughness. In general, large edge hone tools produce higher surface roughness values than small edge hone tools or sharper tools [55]. However, honing is necessary to increase the cutting edge strength, even though the sharpness decreases. When the undeformed chip thickness is small, the cutting edge has a large impact on the process stability and produces a higher surface roughness value [56]. Özel et al. [57] studied the effects of cutting edge preparation, workpiece hardness, feed rate and cutting speed on the surface roughness and resultant forces in the finished hard turning of AISI H13 steel. In their experimentation, the authors found out that honed edge geometry with a honed radius of 10.5 ± 4.0 μm resulted in a better surface roughness than that obtained with tools with a chamfered edge of 20°. Zhao et al. [58] tested three different tools of CBN with honed radii of 20, 30 and 40 μm in hard turning AISI 52100 steels, and the results showed that the edge radius of 30 μm presented the lowest roughness in all tests, and the stability of the cutting process was considered as the major reason for this. Childs et al. [59] experimentally showed, in turning operations of aluminum Al 1100 with cemented carbides, that at lower feed rates, the surface roughness value is proportional to the edge radius and independent of the feed value, although it may be limited by the dynamics of the machine tool. Khan et al. [60] analyzed different edge preparations (chamfer and chamfer plus hone) on wiper inserts for hard turning AISI D2 steels. Their results showed that the wiper configuration is seen to be overriding the effect of tool edge preparation, and no significant difference was observed in terms of tool wear and surface roughness between both edge preparations. In a different study, Muthuswamy et al. [61] studied the combination of cutting edge preparation (chamfer, sharp and honed) with wiper features in face milling operations of high-carbon SAE 1070 steels. In their experimental results, cutting inserts with chamfer and sharp preparation on the cutting edge and a sharp wiper edge presented a superior surface finish than other combinations of edge preparation, such as chamfer-honed, chamfer-chamfer and honed-honed preparations (Figure 6).

- Chip breakers and textures: Chip breakers aid in curling the chips and discharge them quickly, improving chip control. If chips can be broken properly, they will not wrap around the workpiece, reducing vibrations and possible workpiece damage. Therefore, chip breakers can enhance the surface finish, reduce the built-up edge and reduce burrs [36]. Gürbüz et al. [62] studied the influence of different chip breaker geometries on surface roughness generation in turning AISI 1050 steels, and they developed an artificial neural network for prediction purposes, showing that a notable difference among five different chip breakers existed. A more novel approach consists of creating textures at the rake face to be used in conjunction with nanofluids in MQL systems, which reduce the tool wear and improve the surface roughness [63]. Readers may refer to [64] for a review about the influence of chip breaking methods in turning.

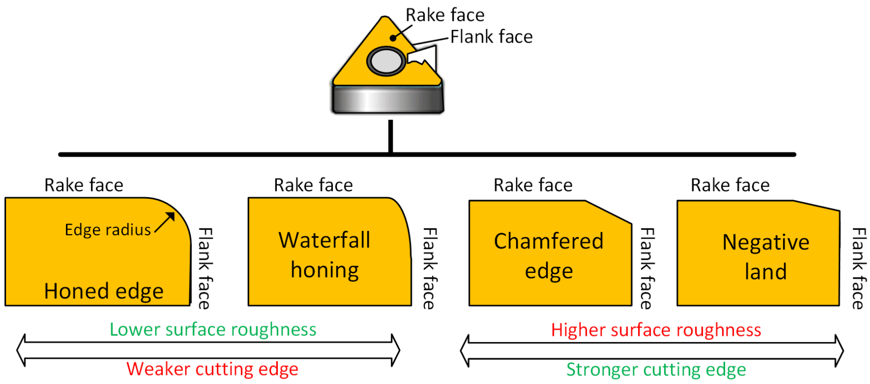


Figure 5. Common tool edge preparations.

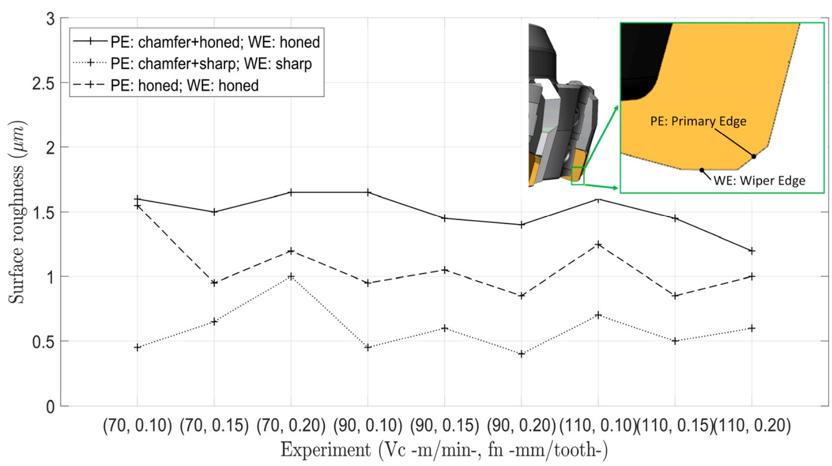


Figure 6. Effect of different cutting edge preparations on surface roughness in face milling of SAE1070 high-carbon steel, adapted from [61].

- Insert/cutter material (material and coating layers): The choice of tool material is very important in order to avoid chip material adhesion, which may produce poor surface finishes. To prevent this phenomenon, a tool grade with low affinity to the workpiece material should be chosen. For machining steel, carbide tools (WC) coated with TiC and TiN are effective. TiC and TiN have a lower solubility to iron than WC, which may help to prevent chip welding. Nalbant et al. [65] reported that increasing the number of coating layers decreases the friction coefficient and parallelly decreases the average surface roughness value of the workpiece. This experimentation was conducted in a CNC lathe using AISI 1030 steels as workpiece materials. The cutting tool materials compared were uncoated WC and WC coated with TiN, TiAlN and AlTiN. The best surface quality was obtained with the TiN-coated multilayered tools—using the CVD method—mainly because of its smaller friction coefficient and thermal conductivity. A similar conclusion was obtained in [66], where uncoated and TiAlN-coated end mills were analyzed in machining Al6061, and the surface roughness was considerably better under the coated tools. However, other researchers did not experimentally find a significant difference, as shown in [67], where micromilling operations in Inconel 718 with different end mill coatings (AlTiN, nACo and TiSiN) were studied. Kumar et al. [68] presented a comparison between Al_2O_3-coated and uncoated carbide inserts in the hard turning of AISI D2 steel. Besides showing the higher performance of the coated insert versus the uncoated one in terms of tool life and surface roughness, the authors also remarked the high surface quality obtained with Al_2O_3-coated inserts that would replace costly ceramic or CBN inserts in hard turning. Cakir et al. [69] compared the resultant surface roughness when machining with two carbide inserts with the completely same geometry and substrate but different coating layers, namely one insert with a TiCN underlayer, an intermediate layer of Al_2O_3 and a TiN outlayer, all deposited by CVD, and another insert with a thin TiAlN layer deposited by PVD. The experimentation was conducted on a CNC lathe and AISI P20 working material, and it was shown that lower surface roughness values are achieved when employing the second insert, which was explained by the higher toughness of the insert and the heat shield effect of the coating. It was suggested that higher toughness may prevent the negative effects of vibrations at lower cutting speeds, whereas the PVD TiAlN coating protects the tool from rapid wear at higher cutting speeds. Darwish [70] compared the performance of ceramic and CBN tools in turning Inconel 718. Under dry conditions and a constant nose radius, the authors showed that there is a 7% improvement in the surface quality at high feed rates and a 10% improvement at low feed rates of ceramic inserts with respect to CBN tools. Chou et al. [71] studied the influence of the CBN content on the surface roughness and tool wear in turning hardened AISI 52100 steel tools. According to their experimental results, tools with low CBN contents produce a better surface roughness value in comparison with tools with higher CBN contents, which was explained by their greater wear resistance and less adhesion. Kumar et al. [72] remarked the importance of tool material on the adhesion tendency of the workpiece material on the rake face, which may produce small welding particles in the insert (i.e., built-up-edge), worsening the surface quality. In general, alumina-based ceramic cutting tools are chemically more stable than high-speed steels and carbides; thus, they present less tendency to adhere to metals during machining, leading to better surface roughness. In addition to all of these aspects, in milling, it has been shown that tool flexibility influences the back cutting phenomenon, since cutting tool deflection lifts the back side of the tool, avoiding the re-cut of the surface [73]. Therefore, carbide end mills that are more rigid than HSS mills tend to more easily present back cutting effects on surface roughness.

3.1.2. Machine Tool/Fixturing Factors

Machine tool/fixturing factors are usually the most difficult to modify for better surface roughness generation, and they are usually seen as fixed factors whose impacts should be minimized by other means. Two main factors may be identified:

- The tilt of the spindle: In milling, if the cutter is perfectly flat against the workpiece, the finished surface is usually recut by the back side of the cutter due to the axial run-out of tool inserts or slight axial deflection. The spindle can also be slightly tilted towards the back side of the tool, which brings the back side of the cutter below the upper side of the cutter, producing the back cutting phenomenon (Figure 7). Furthermore, after the cut, the edges may carry small chips that may scratch the surface at the back side, and the increased cutter contact may induce chatter [74]. These phenomena subsequently reduce the surface quality and tool's life. In order to avoid these phenomena, the spindle may be tilted very slightly in the direction of the feed to provide small relief behind the cut [74]. However, too much spindle tilt may be not compensated during cutting and may produce scallops, which are magnified as cutter diameter increases, producing waviness errors that may affect product performance [75]. The effect of the cutter axis tilt was examined by Ryu et al. [76] in order to model surface generation in flat end milling operations together with other cutting tool imperfections, such as radial and axial run-outs, and eccentricity between the tool's center and spindle rotation center. The experimentation was conducted with a two-fluted tungsten carbon end mill with a 30° helix angle, and the workpiece material used was SS 420J2, a typical mold steel. The results showed that the tilting angle (0.0024° in one of the tools tested) can reduce the peaks in the surface texture. Franco et al. [77] studied the back cutting phenomenon in the face milling of carbon steels with round insert cutting tools. The authors considered axial and radial run-outs and the tool tilt axis and their contribution of front and back cutting to surface roughness. The proposed geometrical model presented good agreement, especially at high feeds, whereas at low speeds, other factors such as vibrations or built-up edge increased model inaccuracy. To monitor the spindle setup tilt and deflection, different methods can be carried out, such as the one proposed by Nguyen et al. [75] based on surface data measured by high-definition metrology.
- Rigidity of machine tool/fixturing/workpiece: The rigidity of the system defined by the machine tool, fixturing and workpiece will influence the stability of the cut and the magnitude of vibrations or chatter generated [34]. Baek et al. [78] developed a dynamic surface roughness model for a face-milling operation of AISI 1041 steels by considering the static and dynamic characteristics of the cutting process. They studied the surface roughness generation of face milling processes and modeled the roughness parameters by considering the run-out effect, the forced vibration occurring in the intermittent cutting process and the static deflection. The authors modeled the face-milling operation as a dynamic system of one degree of freedom while considering the damping and stiffness effects of the cutting tool. The identification of the parameters of the cutting system was obtained by tests of the impact to the tool and workpiece. Childs et al. [59] reported the importance of the dynamics of the machine tool in surface roughness generation. According to their results in the turning operations of aluminum Al 1100 with cemented carbides, at the lowest feeds, Rz becomes independent of the feed and proportional to the edge radius, unless the dynamics of the machine tool intervenes. Additionally, ensuring that the tooth passing frequency and its harmonics do not produce high-frequency responses was shown to be critical to achieve good surface roughness values [79].

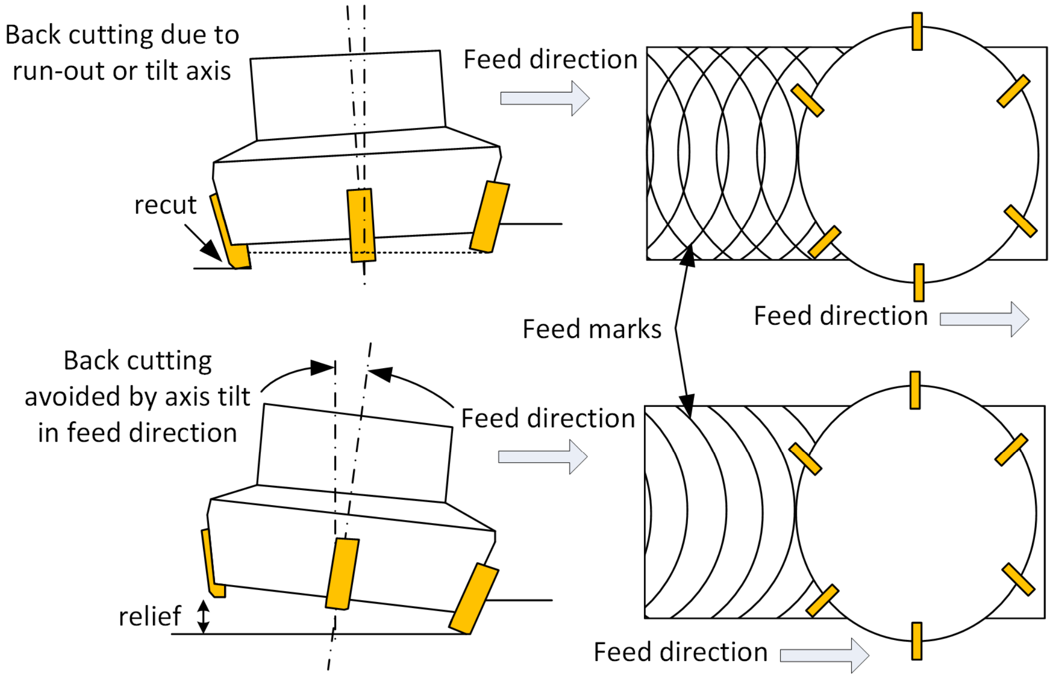


Figure 7. Back cutting effect and slight tilt of spindle in feed direction to minimize it (exaggerated representation).

3.1.3. Workpiece Factors

Workpiece factors are related to the type of material, hardness and initial temperature since these factors will determine the plastic deformation that occurs at the cutting zone. The main effects of these factors are as follows:

- Workpiece materials: The surface roughness may completely differ across different workpiece materials since the particularities of chip formation will depend on material properties. Routara et al. [80] studied the influence of machining parameters on surface quality produced in end milling operations under three different workpiece materials, namely brass, aluminum and mild steel. As expected, the results showed that the response surface models derived for roughness prediction are specific to workpiece materials. Interestingly, the effect of cutting parameters on the roughness parameters was also different for different materials. On the other hand, the use of free-machining additives generally improves machinability since these additives assist in chip formation and lubricate the tool face, reducing adhesion and cutting forces [81]. Recent research works addressed the behavior of composite materials and the influence of process parameters on surface generation and chip formation. They explored mechanisms to mitigate delamination drilling-induced damage, which is detrimental to surface integrity, and explored the use of sustainable fibers with better delamination properties [82].
- Hardness: For the same workpiece material, differences in hardness may contribute notably to surface roughness generation. In general, high hardness values may increase the wear rate and have a negative impact on the surface roughness, whereas low hardness values may produce a built-up edge formation, increasing the surface roughness. Furthermore, milling hard workpiece materials with low entering angles produces high axial cutting forces, which may lead to back cutting and increase surface roughness. Chavoski and Tajdari [83] analyzed the influences of the spindle speed and workpiece hardness on the surface roughness in turning AISI 4140 with CBN tools. From the experimentation, it was observed that, when increasing hardness, there is a decrease in the surface roughness, but when hardness exceeds 55 HRC, the surface roughness increases considerably. Özel et al. [57] reported that a lower workpiece

surface hardness results in better surface roughness when turning AISI H3 steels from 50 to 55 HRC. Similarly, Desale and Jahagirdar [84] studied the influences of different workpiece hardness values (from 55 HRC to 62 HRC) on the surface roughness of tool steels, showing a higher roughness value when hardness increases. Chen [85] studied surface roughness values when cutting hardened steel (45–55 HRC) with different CBN tools and stated that the harder the workpiece material, the lower the surface roughness obtained for a given set of operating parameters.

- Workpiece temperature: The workpiece temperature may influence the cutting process since the material becomes softer and easier to cut. Amin et al. [86] studied the influence of workpiece preheating on surface roughness in the end milling of hardened steel D2. The authors showed that preheating the workpiece produces roughness values that are substantially lower in part due to lower tool wear rates, which is mainly explained by the lower hardness in the preheating state. In recent years, to improve the machinability of hard materials, thermal-assisted machining processes have been proposed, resulting in significant reductions in cutting forces and surface roughness. Baek et al. [87] applied high-frequency induction and a laser beam to heat the workpiece before cutting in milling AISI 1045 steels and Inconel 718. Under both heating methods and materials, the cutting forces were reduced, and the surface roughness improved. Parida and Maity [88] showed that heating Inconel 718 alloys to 600 °C before turning resulted in a decrease of around 20% in the surface roughness with respect to the surface roughness obtained without previous heating. Mac et al. [89] studied the milling process of AISI D2 steels while heating the workpiece up to 400 °C using an induction coil. The resulting surface roughness value obtained in these processes was observed to be 0.1 μm at 400 °C, which is much lower than that obtained using the conventional process, which resulted in 0.17 μm. Similarly, Kalantari et al. [90] analyzed laser-assisted turning operations in Ti-6Al-4V, and they also showed a surface roughness improvement at all machining conditions tested.

3.2. Operational Factors

3.2.1. Cutting Parameters

Operational factors are commonly modified by operators and process planners in order to set the best trade-off between quality, costs and productivity. Among them, cutting parameters are the most straightforward parameters to change in order to reach a specific surface roughness quality. The main cutting parameters with a direct impact on the surface roughness are as follows:

- Cutting speed: In general, it is known that an increase in the cutting speed improves the surface quality since high cutting speeds reduce cutting forces and vibrations, giving a better surface finish [69,91]. Figure 8a shows an example of common surface roughness–cutting speed curves in turning AISI P20 steels, adapted from [69]. Furthermore, the cutting speed is a key parameter to avoid built-up edge formation when machining soft materials, and high cutting speeds are required to reduce the material adhesion [3]. However, other factors may interact, and the final surface roughness may have a different behavior. For instance, Chang and Lu [38] studied a side-milling operation in S45C steels, where they reported that both the feeding direction average roughness and axial direction average roughness increase as the cutting speed increases, which was explained by the increase in the dynamic run-out of the end mill. Nalbant et al. [65] showed that increasing the cutting speed produces a reduction in the average surface roughness for coated cemented carbide cutting tools in turning AISI 1030 steels. However, in the case of uncoated cemented carbide cutting tools, increasing the cutting speed also increases the average surface roughness. In this case, this was explained by the material adhesion, rapid wear-out process and notch wear formations that occur on uncoated cutting tools.
- Feed rate: The feed rate, together with the geometry of the cutting tool nose, is responsible for the geometry of the tooth marks at the workpiece surface. The feed

rate is a dominant parameter in machining, and it produces a high increase in surface roughness when it increases [69]. In fact, the feed rate is the main factor used in kinematic models for surface roughness prediction, and in almost all experimental studies, the feed rate is one of the most significant parameters related to surface roughness. When the feed rate decreases, the surface roughness decreases since the feed marks responsible for roughness are less pronounced. However, at very low feeds, other effects such as side flow arise, and the surface roughness is kept constant or even increases [92]. Figure 8b shows an example of the evolution of the surface roughness with respect to the feed rate from the study presented in [92], where the real and ideal roughness values, according to the feed marks due to the feed rate and nose radius, are represented in turning C45 carbon steels.

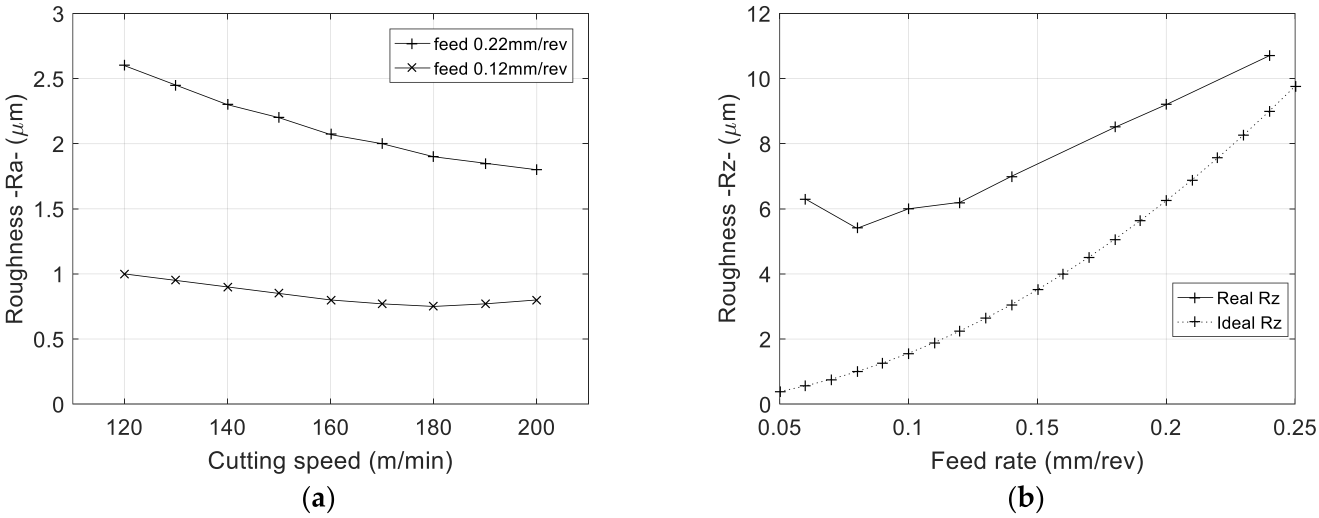


Figure 8. (**a**) Effect of cutting speed on surface roughness in turning AISI P20 steels. Values marked as + and x extracted from the case study reported in [69]. Reproduced with permission from Cakir et al., Journal of Materials Processing Technology, published by Elsevier, 2009; (**b**) effect of feed rate on surface roughness in turning C45 carbon steels. Values marked as + and × extracted from [92]. Reproduced with permission from Grzesik, Wear, published by Elsevier, 1996.

- Axial depth of cut: The influence of the depth of cut on the surface roughness is usually less important than the feed rate or cutting speed. In fact, some investigations show that it is not a significant factor, while other investigations show the opposite. For instance, Tammineni and Yedula [93] studied face milling operations in Al 1050 aluminum alloys, and they showed that surface roughness depends on the cutting factor feed rate and cutting speeds, but the effect of the depth of cut was observed to be unclear. Ding et al. [94] reported that the axial depth of cut contributes the most to the surface roughness in the hard milling of AISI H13. In their experimentation, an end mill operation was studied, and the increase in the axial depth of cut produced an increase in the cutting forces and in the surface roughness, probably because of the vibrations and deflections of the cutter. However, other researchers have presented different trends. Darwish [70] studied finishing turning operations in Inconel 718 alloys and reported that the depth of cut was the second most important factor affecting the surface roughness after the feed rate, and the effect of the depth of cut was more pronounced at high feed rates, where the surface quality improved when the depth of cut increased.
- Radial depth of cut: In milling, the radial depth of cut is also referred to as stepover or cutting engagement. As a general practice, cutting with the full diameter of the tool should be avoided since the cutting starts with a zero chip thickness, which produces higher surface roughness and higher tool wear rates [34]. Therefore, the radial depth

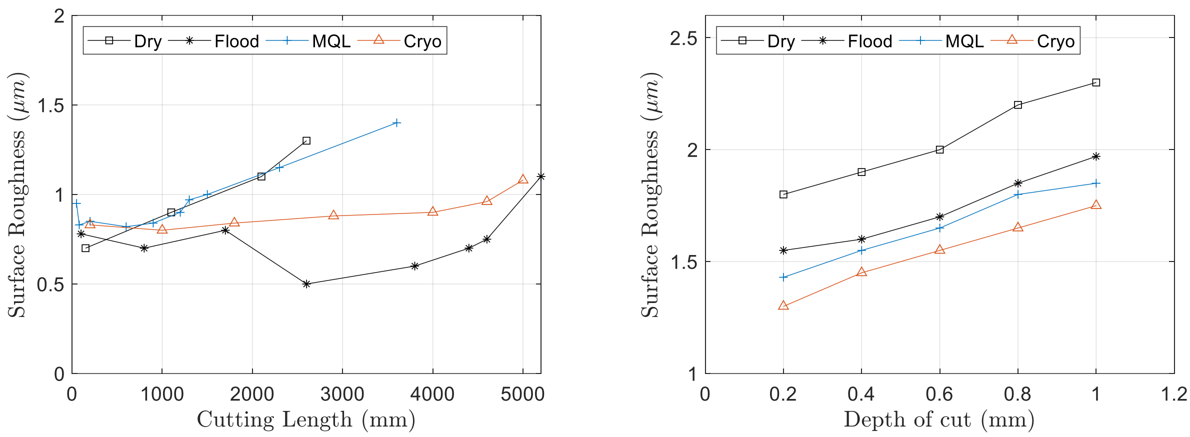
of cut at two-thirds of the tool is commonly recommended in milling operations due to its minimum effect on surface roughness and good material removal rate. However, some researchers have shown the radial depth of cut to have an important role in end milling operations. Jasni and Lajis [91] studied an end mill operation in AISI D2 hardened steels under different cutting speeds and radial depths of cut, and both parameters were equally defined as critical, increasing the surface roughness when the cutting speed decreases or when the radial depth of cut increases, probably due to the increase in cutting forces and tool deflection. A similar trend was observed in [38], where a higher radial depth of cut in side milling operations produced rougher surfaces in S45C steels. More recently, the effect of the relative radial position of the cutter with respect to the workpiece when cutters are bigger than workpiece dimension in flat milling was reported in [95]. This relative position of the cutter produces a predominantly up-milling or down-milling cut, which leads to variations in cutting forces, vibrations and surface roughness. In the experimental results regarding SAE 1045 workpieces, a significant influence existed on surface roughness generation, and the worst surface quality was obtained when the down-milling portion was higher. In ball milling, it is well known that the radial depth of cut is a critical parameter that needs to be set carefully since surface roughness in the transversal direction will be directly related to this value [96] since it acts as the feed rate in that direction.

3.2.2. Process Parameters

Process parameters are a subgroup of operational factors related to the way the cutting process is conducted. For instance, these include milling modes (climb or conventional milling), tool path strategies and cooling/lubricating systems. Their main characteristics and relationships with surface roughness generation are as follows:

- Climb/conventional milling: Climb milling (i.e., down milling) is generally preferred in finishing operations since the cutter starts the cut when the undeformed chip thickness is higher [34]. Unlike climb milling, in conventional milling (i.e., up milling), the cutter starts the cut with a zero chip thickness, causing rubbing or burnishing before the chip can reach its full thickness, which may lead to higher surface roughness [74]. Michalik et al., in their study of thin-walled components from steel C45 [97], recommended the use of the climb milling method to increase the surface quality. Abbas et al. [98] also reported a 22% increase in the surface roughness when conventional milling was used compared to when down milling was used in milling single slots in AISI P20 mold steels.
- Cutting strategies: With the use of Computer-Aided Manufacturing (CAM) systems, many different and complex cutting strategies are easily adopted in conventional machining operations, such as trochoidal, trichoidal, follow-part, zig, zig-zag, plunge, etc. Some investigations have shown that the selected strategy can have a significant impact on the surface roughness. Karkalos et al. [99] analyzed the surface roughness quality of two strategies for slot machining in Al 6082 alloys: conventional and trochoidal. The results showed that the trochoidal strategy provided a superior surface quality. Uzun at al. [100] studied four different strategies in milling AISI X210Cr12 steels, namely trochoidal, follow part, zig and zig-zag, and observed that the best surface roughness value was achieved under the follow part and trochoidal strategies.
- Coolant: Besides being used to reduce the temperature at the tool–chip interface, cutting fluids are employed in machining operations to reduce the adhesion of the work material to the edges of the tool, improving the surface roughness. Cutting lubricants are particularly effective at low cutting speeds and feed rates where the emergence of the built-up-edge phenomenon may be reduced. From previous works in turning steels [101,102], it can be seen that under dry cutting strategies, the adhesion of the work material to the tool has the highest adhesion rate, increasing the surface roughness. However, the quantity of the adhered material is reduced under flood cooling. Under other coolant strategies, such as minimum quantity lubrication (MQL),

the amount of material adhered is commonly higher than that under flood cooling but lower than dry machining [103]. Yan et al. [104] proved that MQL systems, when used in milling 50CrMnMo steels, can reduce tool wear, improve tool life and generate a better surface finish mainly by reducing the friction in the chip–tool and workpiece–tool interfaces, i.e., reducing the adhesion. A maximum quantity of lubricant from which there is no additional reduction in the adhered material has also been identified [103]. Furthermore, MQL requires a correct setup in terms of both the flow rate and nozzle position. Hadad and Sadeghi [102] found that the nozzle position may be critical to MQL performance in turning AISI4140 steel alloys, and lower surface roughness values can be achieved through the supply of oil mist to both the rake and flank faces. Similarly, Duan et al. [105] showed the influence of the nozzle position of MQL systems on the surface roughness of Al 7050 alloys, and Mia et al. [106] experimentally showed the evolution of the lubrication effectivity according to the flow rate applied. Yalçin et al. [107] applied air cooling to reduce adhesion in milling soft materials (annealed AISI 1050, 10 HRC), and they showed that air cooling can be used for the cutting operation for soft steels as an alternative to liquid cooling. Jerold and Kumar [108] studied the use of a CO_2 cryogenic coolant to reduce the cutting temperatures to lower and improve the surface roughness. They compared the machining performance of the cryogenic coolant to dry and wet machining in turning AISI 1045 steel. The authors reported that the use of cryogenic cooling reduced cutting temperatures by 5–22% and improved the surface finish by 5–25% compared to when using wet conditions. In [109], dry, flood, MQL and cryogenic cooling were compared in the turning of a 15-5-PH SS alloy, showing a better performance of flood cooling in terms of the surface roughness throughout tool wear evolution (Figure 9a). Sivaiah and Chakradhar [110] compared the same cooling techniques but at different depths of cut in turning 17-4 PH stainless steel, and they showed that surface roughness differences among cooling strategies may reach 75–100%, where the best performance was given by cryogenic cooling systems, whereas the worst performance was seen in dry machining (Figure 9b). In general, oil-based cutting fluids containing fatty acids generate low friction coefficients during cutting at low cutting temperatures, and extreme pressure additives such as chlorine and sulfur compounds are effective at higher cutting temperatures, lowering the friction coefficient, which leads to a reduction in adhesion and better surface roughness [7]. Yin et al. [111] compared the performances of different vegetable oils (cottonseed, palm, castor, soybean and peanut oils) in relation to cutting forces and surface roughness in milling AISI 1045 steels and observed that using palm oil, due to its high viscosity and small contact angle, leads to better surface roughness values. However, fluid penetration between the tool face and the chip may depend on the cutting speed, with the lubrication being more effective at lower speeds. The effect of using solid lubricants, such as graphite and molybdenum disulphide, on hard turning AISI 52100 steel with ceramic inserts was examined in [112]. Solid lubricants, although more difficult to apply, also produce lower surface roughness values in comparison to dry hard turning due to the reduction in material adhesion to the cutting tool. Other papers addressed the poor machinability of composite materials and the use of eco-friendly lubrication systems, like ultrasonic atomization, to reduce carbon emissions [113] and cryogenic cooling conditions [114–116].



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

Figure 9. (**a**) Impact of different cooling/lubricating systems on surface roughness: (**a**) roughness and tool wear evolution (cutting length) in turning of 15-5-PH SS alloys, adapted from [109]. Reproduced with permission from Khanna et al., Tribology International, published by Elsevier, 2006; (**b**) roughness and different depths of cut in turning 17-4 PH stainless steel, adapted from [110]. Reproduced with permission from Sivaiah and Chakradhar, CIRP Journal of Manufacturing Science and Technology, published by Elsevier, 2018.

3.3. Processing Factors

Processing factors are related to those that are specific to the cutting phenomenon. These factors are highly related to setup and operational factors. For instance, a built-up edge phenomenon may appear if the cutting speed is too low, with a very high impact on the surface roughness. However, when using the correct cutting tool and cutting parameters, a BUE may not appear. The following relevant processing factors can be found:

- Built-up edge (BUE): BUE formation may be produced at the tip of the tool, as shown in Figure 10, modifying the tool nose radius and generating higher surface roughness values. The primary cause of a BUE in machining is the adhesion of workpiece material to the tool's cutting edge during machining operations. The high pressures and temperatures at the cutting interface cause this adhesion. Various factors, including the material being machined, cutting conditions and tool material, can influence the exact mechanisms responsible for the development of a BUE. This phenomenon is particularly important when machining soft materials or using low cutting speeds, although other factors, such as tool geometry and material, cutting conditions or use of lubricants, may interact [117]. Figure 11 shows the influence of different workpiece materials and cutting speeds on the surface roughness. As it can be noticed, the surface roughness increases when the cutting speed decreases due to BUE formation. Furthermore, the BUE also plays an important role in tool wear, which, in turn, is related to surface roughness [7]. In order to reduce BUE formation, it is recommended to increase the cutting speed, use cutting tool grades with less adhesion tendency and use coolants [36]. Increasing the rake angle, using more lightly honed inserts and reducing the undeformed chip thickness are also effective ways of controlling the BUE roughness at relatively low cutting speeds [7].

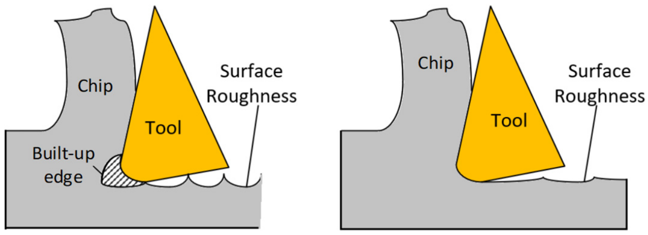


Figure 10. Built-up edge formation and differences in surface roughness generation.

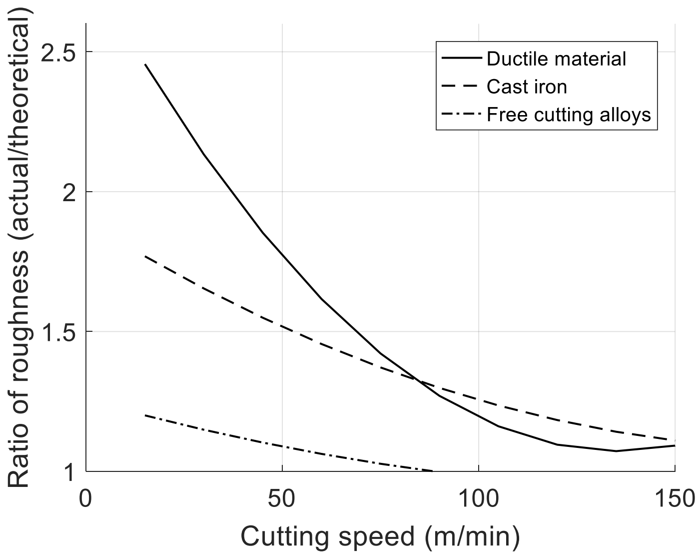


Figure 11. Examples of surface roughness evolution with respect to cutting speed due to BUE formation. Adapted from [3]. Reproduced with permission from Stephenson and Agapiou, Metal Cutting Theory and Practice, published by Marcel Dekker Inc, 1997.

- Vibrations: Vibrations may have a clear impact on dimensional accuracy, surface roughness, and tool life. Many research works have analyzed the effect of vibrations on surface roughness. Baek et al. [78] studied the generation of surface roughness profiles in face milling operations with AISI 1041 workpiece materials and modeled the process while considering both static and dynamic components. The authors derived a surface roughness model for prediction purposes based on the relative displacement between the workpiece and the cutting tool while considering cutting forces, insert run-out error, insert edge profile and cutting conditions (cutting speed, feed rate and depth of cut). Chang et al. [118] proposed measuring the vibrations from the spindle using a capacitive displacement sensor to predict the surface roughness. The system was modeled as a cantilever beam, and the first mode shape was assumed to be the main vibration that determines surface roughness generation. A simple linear model between the measured surface roughness and the roughness calculated using spindle motion was developed. Similarly, Abouelatta and Mádl [119] reported a correlation between vibrations and surface roughness in turning free-cutting steel, and a surface roughness model based on vibrations and cutting parameters was built for prediction purposes with a good performance. Wang et al. [120] investigated the influence of tool-tip vibration on the surface roughness in ultraprecision single-point diamond turning of copper alloys. Their results showed that the relative tool work displacement during the turning process was mainly due to the high-frequency tool-tip vibration, and it was considered as the dominant factor affecting the roughness of the machined surface. In order to reduce tool vibration and improve the surface roughness, it is necessary to provide sufficiently rigid tooling and workpiece fixtures, and it is especially necessary to limit the overhangs of tools such as boring tools or end mills [57]. Besides using rigid tooling and fixturing devices, vibrations may be reduced using large entering angles, positive rake angles and a low depth of cuts that is larger than the nose radius. The effects of vibrations may be accentuated if the frequency of any component within the machine tool/workpiece system approaches their respective natural frequencies. Under these situations, the interaction between the chip removal and the structure of the machine tool may cause instability in the cutting process with a direct impact on the surface texture. This phenomenon, called chatter, generally occurs under heavy-duty cutting where high depths of cut are the most significant cutting parameters for chatter generation [121]. The cutting process is more stable when the chip width is smaller, and thus, there is a limiting depth of cut where chatter starts to occur. This limiting value depends on many other factors that influence cutting stability. For instance, in high-speed machining, the stability of the cut increases at high spindle speeds, and a higher depth of cuts may be applied without chatter generation. Tool wear is another factor that may result in a drastic change in the dynamics of the cutting process. Tlusty [122] showed that cutting stability may be reached by the damping effect of tool flank wear. Sisson and Kegg [123] found that a high stability at low speeds is caused by the damping generated at the tool–workpiece interface, which is affected by the radius of the tool nose, the clearance angle and the cutting speed. Other factors, such as the preparation of the tool cutting edge; the dynamic characteristics of the structure; the workpiece material, cutting speed and feed; and the geometry of the tool can have important influences on the damping produced by the cutting process [121]. Seguy et al. [124] studied surface roughness generation in thin wall parts due to chattering. Amin et al. [86] showed that in machining hardened steels, preheating workpieces have great potential to lower chatter. Despite the expected negative influence of vibrations, other authors have investigated the possibility of improving the surface roughness if a tool is assisted with high-frequency vibrations [125]. Due to high-frequency vibrations, the tool periodically loses contact with the chip, leading to reductions in machining forces, friction and temperature in the cutting zone. Thinner chips are formed, and there are improvements in cutting stability, surface finish and tool life in comparison to conventional machining. In a previous paper, the authors also reported a surface roughness improvement in turning operations by applying a piezoelectric transducer to excite the system [126].

- Tool wear: Many research works have shown that an increase in tool wear produces an increase in surface roughness over cutting time [79,127]. However, many others suggest that at the beginning of the wear-out process, the roughness values exhibit a falling and rising trend with the machining time [85,128] (Figure 12a). Yan et al. [104] observed that high roughness values are generated when the cutting insert is totally new. When the insert starts to be worn, the radius of the tool nose increases and the surface roughness is improved, reducing the teeth marks. Afterwards, a high increase in the tool wear produces irregularities in the nose radius, and the surface roughness rapidly increases. Other studies have shown that the forces and the surface roughness tend to increase as the tool wear increases [60,129] (Figure 12b). Since the cutting temperature is the main factor that influences tool wear progression, coolants are commonly used to reduce the tool wear rate.
- Plastic side flow: The surface roughness is closely related to the feed rates. However, when low or very low feed rates are applied, the shearing mechanism is replaced by a ploughing mechanism since the chip is not thick enough for removal. Thus, the material is plastically deformed rather than forming a sheared chip, and the accumulation of the deformed material around the tool produces a rougher surface, as shown in Figure 13 [130]. Kishawy et al. [131] studied hard turning operations in 52,100 steels and they showed that more side flow is generated when a higher nose radius is used, increasing the surface roughness. Similarly, Thiele and Melkote [130] proved that a larger cutting edge radius results in more ploughing, and thus, more

material is pressed under the tool, which leads to an increased surface roughness. Zong et al. [132] focused their work on single-point diamond turning operations with pure copper workpieces, and they studied surface roughness generation while considering the plastic side flow together with the elastic recovery of the machined material. In their study, they observed that the feed rate, cutting edge radius, corner nose radius and rake angle act as factors that influence surface roughness generation. Experimentally, it has been proven that the quantity of side flow increases with a decrease in the rake angle and with an increase in the depth of cut [133,134]. In general, there is a critical ratio of uncut chip thickness, denoted as h_m, to edge radius, r_e, below which chip formation changes from cutting to ploughing [135]. Experimental and theoretical studies have indicated the critical value of h_m/r_e to be between 0.1 and 0.5, although it depends on the workpiece material and edge rounding of the cutting insert [135].

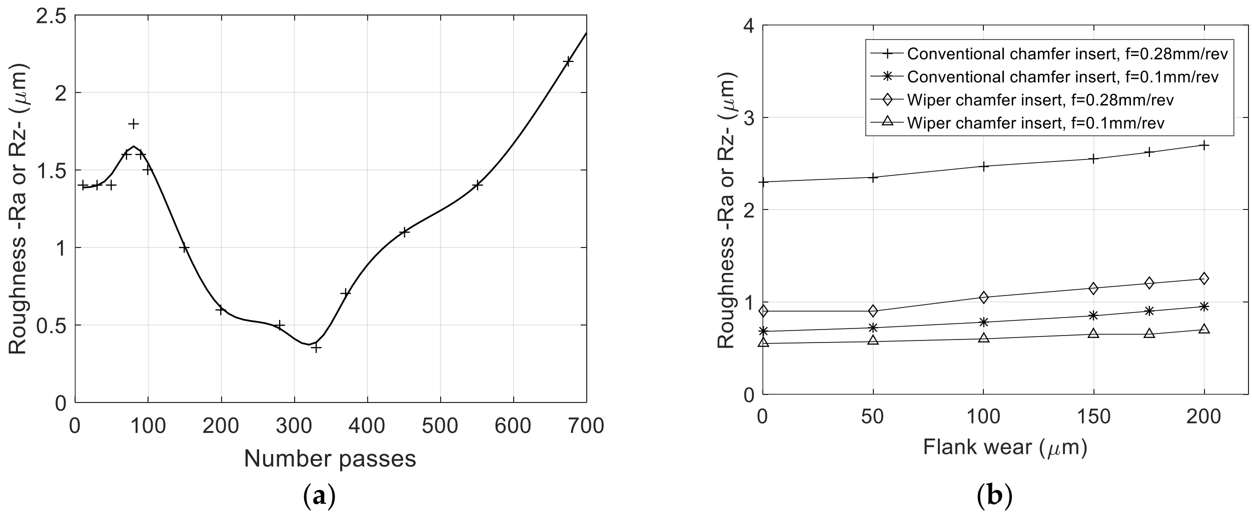


Figure 12. Common types of surface roughness evolution with tool wear: (**a**) roughness in face milling with carbide inserts and workpiece material 4140 preheat-treated steels. Values marked as + extracted from the case study reported in [128]. Reproduced with permission from Jiang et al., Tribology Transactions, published by Taylor & Francis, 2008; (**b**) different roughness curves in hard turning of AISI D2 steels with wiper and conventional alumina inserts, adapted from [60]. Reproduced with permission from Khan et al., Journal of Manufacturing Processes, published by Elsevier, 2018.

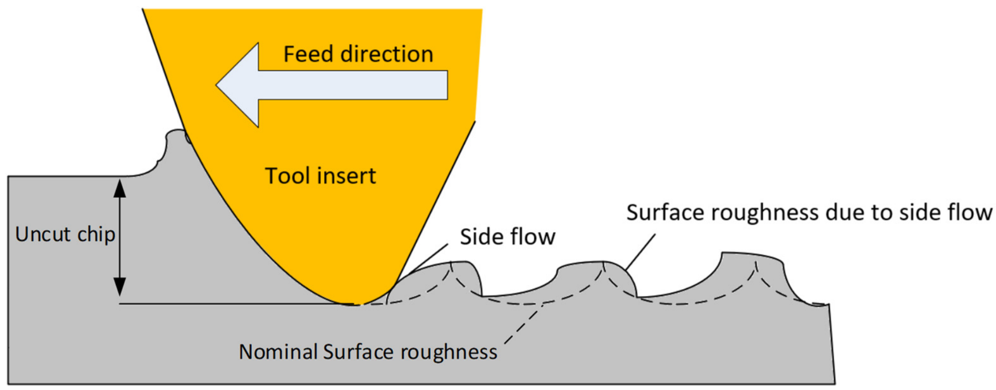


Figure 13. Plastic side flow in machining.

4. Linking Surface Roughness and Sustainability: Case Studies

Machining sustainability has been widely studied, and many different strategies have been proposed to reduce resource consumption and environmental impact. The most common approaches to improve machining sustainability are related to cooling/lubrication systems and cutting parameter optimization to reduce CO_2 generation [10,12]. Although many other aspects have been studied to improve machining sustainability, less attention has been paid to the factors related to surface roughness generation, which are directly related to the quality output of the process. Therefore, by acting on these factors, a specific surface roughness can be ensured while minimizing the consumption of resources.

Three levels of actions may be identified: basic, intermediate and advanced. Basic actions are related to changes in setup factors, which may be conducted in a straightforward manner. For instance, these actions may include the use of proper cutting inserts that allow for higher material removal rates while keeping a good surface roughness; the use of tool materials that reduce the adhesion of the material, improving the surface roughness and avoiding lower material removal rates and scraps; the use of inserts with proper edge preparation that allow for lower surface roughness rates at higher production rates, etc. Note that, in general, high material removal rates lead to lower specific cutting energies, i.e., a lower kJ per volume of material is removed, which means less kg of CO_2 equivalent.

The intermediate level would refer to changes in the operation factors that may require a more in-depth study. For instance, this may include changes in the coolant/lubricating systems or the optimization of cutting parameters, which may require experimental data or some tests to set the operating parameters and ensure benefits are obtained from the change.

Finally, the advanced level would refer to the implementation of systems that can monitor the processing factors and thus act properly on the system to optimize the use of resources while ensuring surface roughness specification. This level may be related to the use of sensors and monitoring systems that can estimate the influence of processing factors, such as tool wear, vibrations and built-up edge generation, and then adapt the cutting conditions or call for an early tool replacement in order to optimize the machining performance and avoid the need for scraps or parts to be reworked.

To illustrate these levels of acting and how studying and acting on surface roughness factors can notably improve machining sustainability, three examples are provided in this section. First, an example is shown where only a change in the type of cutting tool insert, from a conventional insert to a wiper insert geometry, produces a notable impact on productivity, reducing power consumption and, thus, CO_2 generation. Secondly, a change in the coolant system is highlighted as a straightforward method to improve sustainability by increasing tool life and productivity with CO_2 reduction. Finally, a third example shows the high impact that could be achieved if grinding processes can be replaced or minimized when the surface roughness can be controlled during conventional machining operations. It should be mentioned that the second and third examples are extracted from a previous research work by the authors in the mold manufacturing sector, and detailed information can be found in [136].

4.1. Insert Change Geometry

A straightforward improvement in machining sustainability can be achieved by using wiper inserts in milling operations. As shown above, the edge geometry of wiper inserts allow for the feed rate to be increased while the surface roughness remains low in comparison with conventional inserts. To illustrate the impact on machining sustainability, consider the example shown in [137], where the use of two different inserts, namely a wiper insert and a conventional one, is studied in hard turning operations in AISI 4340 steels (Figure 14). In this work, the estimation of the surface roughness for each insert is explicitly stated as follows:

$$Ra_{wiper} = 0.518 + 0.21 \times f_n + 0.076 \times V_c + 0.032 \times a - 0.017 \times f_n \times V_c - 0.007 \times f_n \times a - 0.008 \times V_c \times a - 0.011 \times f_n^2 - 0.029 \times V_c^2 - 0.005 \times a^2, \quad (1)$$

$$\begin{aligned} Ra_{conventional} = \; & 1.431 + 0.589 \times f_n - 0.147 \times V_c + 0.085 \times a \\ & -0.215 \times f_n \times V_c - 0.024 \times f_n \times a - 0.039 \times V_c \times a \\ & -0.026 \times f_n^2 - 0.127 \times V_c^2 - 0.017 \times a^2 \end{aligned} \quad (2)$$

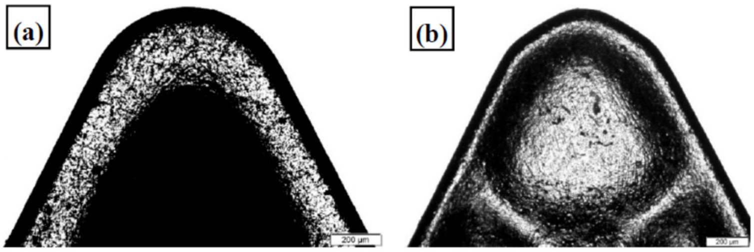


Figure 14. Conventional (**a**) and wiper inserts (**b**) analyzed in [137] and applied in case study 1. Original figure from [137] under Creative Commons CC BY 4.0 license.

As can be seen in Figure 15, the evolution of the surface roughness is different for both inserts, and the wiper insert presents lower roughness values. Thus, replacing the conventional insert with the wiper insert and increasing the feed rate is a straightforward solution to reduce power consumption and the kg of CO_2 equivalent. The power consumption in machining operations is estimated as follows [138]:

$$P_{machining} = P_c + P_{idle} \tag{3}$$

where P_{idle} refers to the power consumption of the machine tool in its idle state and P_c is the cutting power required in the operation, which includes the energy for material removal, the energy for moving the machine tool table and the energy for rotating the spindle. Considering only the material removal energy, the cutting power is estimated as follows [34]:

$$P_c = \frac{Q \times k_c}{60 \times 10^3} \tag{4}$$

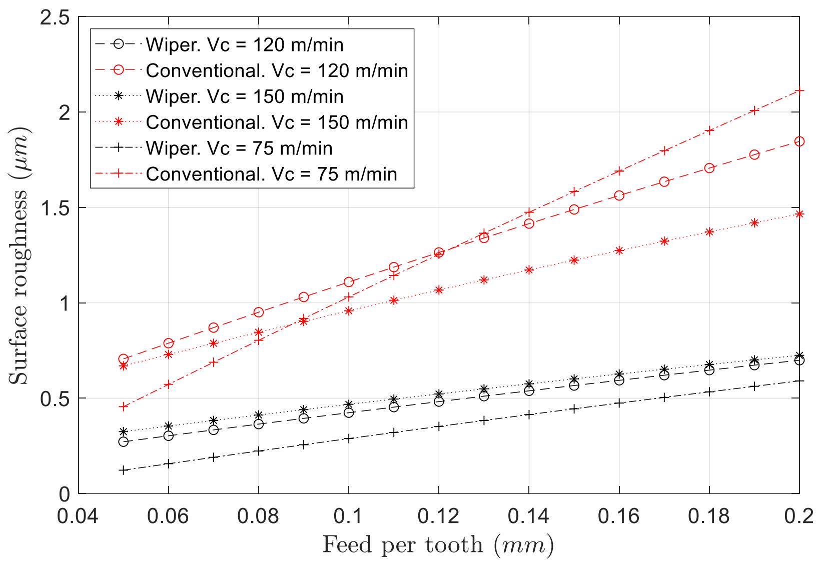


Figure 15. Surface roughness for conventional and wiper inserts for different cutting parameters according to regression models in [137].

In this expression, Q refers to the material removal rate, calculated as follows [34]:

$$Q = V_c \times a \times f_n \tag{5}$$

k_c is the specific cutting force that is estimated as follows [34]:

$$k_c = k_{c1} \times \left(\frac{1}{h_m}\right)^{m_c} \times \left(1 - \frac{\gamma_o}{100}\right) \tag{6}$$

The value of k_{c1} refers to the specific cutting force when cutting an undeformed chip thickness of 1 mm, h_m is the undeformed chip thickness, and γ_0 is the rake angle of the insert. The undeformed chip thickness depends on the feed per revolution f_n and the entering angle κ according to the following expression [34]:

$$h_m = f_n \times \sin \kappa \quad (7)$$

However, since the feed rate is higher under wiper inserts, the total energy consumption is lower when using wiper inserts. Energy consumption, which is directly related to the kg of CO_2 emission, depends on the total machining time, and thus, it can be estimated as follows:

$$E_c = P_c \times t_c \quad (8)$$

For the sake of simplicity, the machining time, t_c, is expressed by only considering the cutting movements, and thus, it can be defined as follows:

$$t_c = \frac{L_c}{N \times f_n} \quad (9)$$

where L_c is the length of the cut in mm, and N is the spindle speed in rev/min. To illustrate the impact of the change in the cutting tool geometry on the energy consumption, consider that the hard turning process is conducted at 120 m/min and 0.05 mm/rev with the conventional insert. The same surface roughness quality can be achieved at the same cutting speed but by increasing the feed rate up to 0.2 mm/rev according to the roughness models shown in Equations (1) and (2) and Figure 15. Both cutting inserts present an entering angle of 45°, a rake angle of 6° and a specific cutting force (k_{c1}) of 2000 N/mm^2 [34]. Under these values, the reduction in energy consumption by using wiper inserts instead of conventional inserts is shown in Figure 16 as a function of the idle power consumption of the machine tool. As can be seen, since the feed rate is increased from 0.05 to 0.2 mm/rev, the time required for machining the same number of parts in a batch is reduced by up to 75%. However, although higher feed rates reduce the specific cutting force, the chip thickness is higher, and thus, the cutting forces and power consumption are higher when wiper inserts are applied. Taking into consideration the power consumption at the idle state, the evolution of the reduction in kg of CO_2 for this case study is presented in Figure 16, where the highest reduction is given at higher power consumptions at the idle state, with a maximum value related to the increase in productivity, a 75% value.

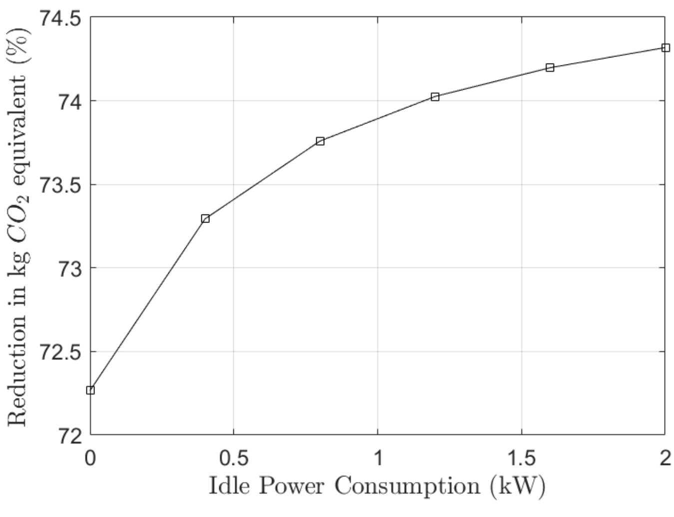


Figure 16. Reduction in kg of CO_2 equivalent when replacing conventional inserts by wiper inserts depending on the machine tool power consumption at its idle state. Squares refer to computed data from the equations.

It should be noted that the efficiency of the insert geometry change in terms of sustainability depends on the tool wear evolution on the wiper insert, which has been assumed to be the same for both wiper and conventional inserts. The same authors in a subsequent work reported that the wiper inserts presented a similar tool wear behavior than the conventional ones [139]. However, it should be noted that other research works present very different tool wear behaviors, with some of them even showing that for specific operations, the wiper inserts form a built-up edge, which decreases their tool lives notably with respect to conventional tools [140]. Furthermore, even when assuming that wiper and conventional inserts present similar tool wear evolution under the same cutting operations, it should be noted that wiper inserts are used at higher feeds to increase productivity, which is likely to reduce their tool lives. This is shown in the well-known extended Taylor's expression [3]:

$$T_{life} = \frac{C}{V_c^{n_1} \times f_z^{n_2}} \tag{10}$$

where C, n_1 and n_2 are coefficients that depend on a particular tool–workpiece combination. Therefore, to consider the effect of an increase in the tool wear when using wiper inserts, the energy consumption equation shown in Equation (8) is changed as follows:

$$E_c = P_c \times t_c + E_{insert} \times n_{inserts}, \tag{11}$$

where E_{insert} is the energy required to manufacture a carbide insert in kJ, which is estimated as 1500 kJ [11], and $n_{inserts}$ is the number of inserts used for machining a batch, calculated as follows:

$$n_{inserts} = \frac{N_{parts} \times t_c}{T_{life} \times n_{edges}} \tag{12}$$

In the above expression, N_{parts} refers to the total number of parts in a batch, and n_{edges} is the number of edges that can be used per insert. Considering the reduction in tool life when a wiper insert is used, Figure 17 shows how the reduction in energy consumption (i.e., kg of CO_2 equivalent) evolutes as a function of the ratio between the conventional insert's tool life under low feed rates and the wiper insert's tool life under higher feed rates. As can be seen, even if the reduction in tool life is very high, for instance, a ratio of 0.25, which means that the wiper insert's tool life is one-fourth the conventional insert's tool life, the reduction in energy consumption is very significant in the case that power consumption at the idle state is not negligible (values around 35% reduction if the idle consumption is 0.5 kW, which is a conservative assumption for most machine tools), which remarks the importance of increasing the feed rate to reduce the cutting time while keeping low surface roughness values under the use of wiper inserts.

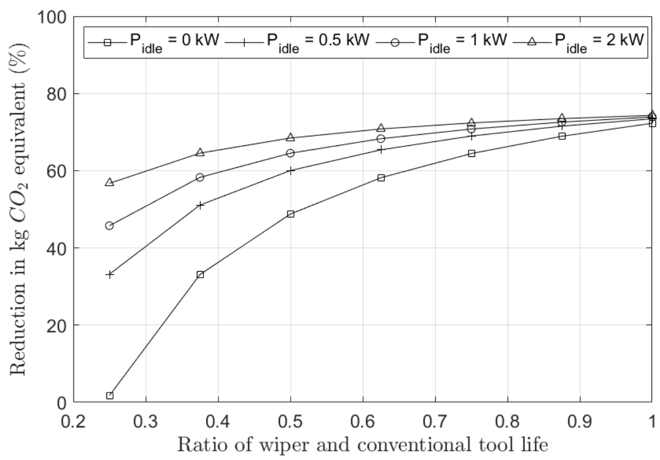


Figure 17. Reduction in kg of CO_2 equivalent when replacing conventional inserts with wiper inserts depending on the ratio of wiper insert tool life and conventional insert tool life.

Summary: Changing a conventional insert to a wiper insert multiplies the material removal rate by a factor of 3 or 4 while maintaining the surface roughness quality. The use of wiper inserts notably reduces the CO_2 equivalent generation, and it can easily reach reductions of 30–50% if the wipers do not show built-up edge formation or other issues.

4.2. Lubricating Change

Another change in the machining process that can notably improve machining sustainability is the change in the cooling/lubricating system. As an example, consider the machining of the punch part shown in [136] related to mold manufacturing (Figure 18). A common approach to machine this part made of DIN C45 steel is conventional milling with air cooling to remove chips and avoid the effect of thermal fatigue and cracking due to flood cooling. However, the potential use of an MQL system can increase tool life and surface quality, as presented in [136]. The air-cooling strategy is conducted under a cutting speed of 160 m/min and a feed per tooth of 0.4 mm. The introduction of an MQL system with 15 mL/h of lubricant consumption allowed the cutting speed to be increased to 200 m/min and the feed rate to be increased to 0.5 mm/tooth while keeping a similar tool life and surface roughness. In this example, the cutting tool used is a face cutter of 52 mm in diameter with five octagonal/round carbide inserts, and the rest of the cutting parameters for both scenarios are a radial depth of cut that is 75% of the diameter and an axial depth of cut of 1 mm.

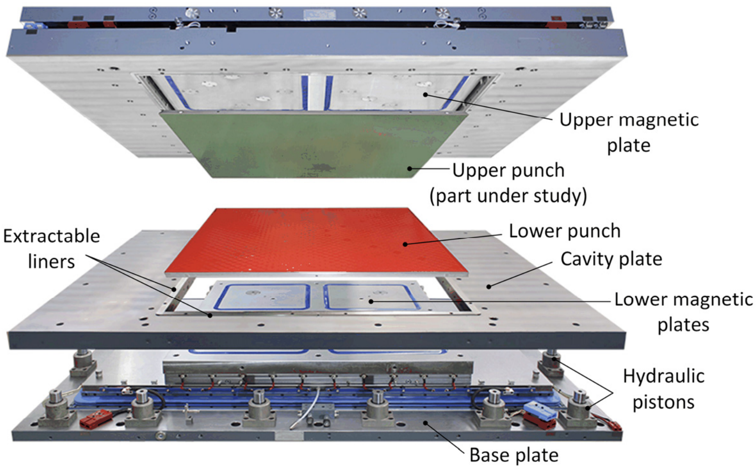


Figure 18. Typical mold applied in manufacturing tile lines. Courtesy of Macer SL. The machining process of the part "upper punch" is analyzed in [136], and the data are used for case studies 2 and 3.

For this milling application, the material removal rate is calculated as follows [34]:

$$Q = a_e \times a_p \times v_f \tag{13}$$

where a_e is the radial depth of cut, a_p is the axial depth of cut, and v_f is the feed rate of the cutting tool in mm/min. By applying the same equations as those used for the turning operations in case study 1, the power consumption is evaluated in a straightforward manner. In this example, the power consumption under the MQL system is given by a linear regression as follows [136]:

$$P_{cons} = 6127 - 0.4214 \times V_c - 3616 \times f_z + 83.13 \times V_c \times f_z \tag{14}$$

Therefore, the cutting power consumption under the MQL operation is 12.55 kW, while for air cooling, the power consumption, assuming a similar behavior, can be estimated as 9.9 kW. For the batch studied in [136], the time required for machining under air cooling is 3207 min, whereas the time needed under the MQL system is 2052 min. As a result, the application of the MQL system reduces the total kg of CO_2 equivalent by 36% at the milling stage, assuming that the differences in energy consumption from the air-cooling system and the MQL system are negligible. Note that the research work in [136] states a reduction of 17% in kg of CO_2 equivalent in the punch manufacturing process since it is considered to consume both milling and grinding power.

Summary: A change in the lubricating systems from dry/air cooling to MQL systems can easily improve the surface roughness, which may lead to higher removal rates. Thus, the MQL used may lead to a significant reduction (15–30%) in kg of CO_2 equivalent.

4.3. Feed Rate Optimization and Early Tool Replacement to Eliminate Secondary Operations

A more efficient strategy to improve machining sustainability can be conducted if surface roughness monitoring is possible, which can lead to the control of the surface roughness to ensure a specific quality requirement and reduce or even replace expensive grinding operations. If the surface roughness can be assumed to be a repeatable process, where surface roughness evolves over time, due to the natural wear process of the insert being relatively known and stable, a roughness monitoring system may be substituted with an early tool change replacement strategy to ensure surface roughness specifications.

An example is provided in the same case study presented by the authors in [136]. The punch part presented above requires, in addition to milling, a grinding process to ensure a surface roughness lower than 1.5 μm is obtained. Two options are compared with the same MQL lubricating system, namely one with a maximum removal rate during milling with a subsequent grinding operation, and a second option where the surface roughness is controlled under proper cutting parameters and an early tool change replacement strategy, which avoids the final grinding step. In this case, the cutting parameters are obtained by minimizing a function cost, which is a costing function. For the first option, the milling operation is set up with the parameters of a cutting speed of 200 m/min and a feed rate of 0.5 mm/tooth. For the second option, the cutting parameters are set up to 200 m/min and 0.15 mm/tooth for the cutting speed and the feed rate, respectively, and an early tool change strategy is set to 40% of the tool life for the first option, which is equivalent to change the tool at approximately 0.15 mm of tool flank wear. Although the productivity at the milling stage decreases with an important cost of cutting tools, the elimination of the grinding process highly improves the global sustainability of the process. The power consumption at the grinding process is estimated as follows [141]:

$$P_{grinding} = E_s \times Q_g + P_{idle} \tag{15}$$

where E_s is the specific energy for grinding, which can be estimated as 40 J/mm^3 according to [141], Q_g is the material removal rate at grinding and P_{idle} is the power consumption of the grinding machine at the idle state. By analyzing the kg of CO_2 equivalent due to the total power consumption from both the milling and grinding processes and the kg equivalent of CO_2 related to cutting tools (1.5 MJ/insert for carbide inserts and 50 MJ/kg for aluminum oxide for grinding wheels), the second option with an early tool replacement leads to a reduction of 67% in kg of CO_2 equivalent. Furthermore, the elimination of the flood cooling at the grinding state contributes to 3357 L of water being saved annually, although the MQL system, which is set up to 50 mL/h, requires the consumption of 6.1 L of vegetable oil per year.

Summary: A critical step in machining sustainability is the elimination of secondary operations. The implementation of early tool changes, cutting parameter optimization or online monitoring systems may ensure part quality without costly and unsustainable grinding operations. If correctly applied, high reductions (40–60%) in kg of CO_2 equivalent and water consumption can be achieved.

5. Conclusions

The interplay between surface roughness and sustainability in machining processes has emerged as a critical focal point in contemporary manufacturing. As industries increasingly pivot towards environmentally conscious practices, optimizing surface roughness not only enhances product quality but also aligns with sustainable objectives by reducing material waste, energy consumption and environmental impact.

This work presented a review of the factors that affect surface roughness generation in machining (turning/milling) processes. Up to twenty-five different factors were identified, which were classified as setup factors (cutting tool, machine tool/fixture and workpiece factors), operational factors (cutting and process parameters) and processing factors (those related to the resulting cutting process, such as built-up edge, chatter or tool wear).

The importance of understanding surface roughness generation to improve machining sustainability was presented under three case studies. The first case showed a reduction of approximately 75% in CO_2 equivalent by using a wiper insert instead of a conventional insert in hard turning. The second case study illustrated a reduction of 35% in kg of CO_2 equivalent through a change from air cooling to MQL cooling in milling a punch in the tile mold industry. The third case showed the high impact that can be achieved if grinding processes can be replaced by controlling the surface roughness in previous milling/turning operations. In the presented case, an improvement of 67% in kg of CO_2 equivalent and the elimination of water consumption required in flood cooling were obtained by optimizing the cutting operations and using an early tool change replacement instead of conventional milling and subsequent grinding operations.

The future trends in sustainable machining seek to optimize manufacturing resources while ensuring part specifications at both the macro and micro geometric levels. The major research directions in this field are as follows.

- The design of special geometries in cutting inserts. Different edge preparation techniques and textures on rake faces are being actively investigated to reduce the friction coefficients and cutting temperatures. Textures with different sizes and patterns are being machined using a laser or other methods and subsequently tested to improve machining performance.
- Advanced cooling and lubrication systems. Cooling/lubrication systems are bring continuously improved to reduce cutting temperatures and tool wear and limit their impact on surface roughness. Intensive research has been conducted on MQL systems with nanofluids (vegetable oils with small percentages of dispersed nanoparticles, such as carbon nanotubes, molybdenum disulfide or silica nanoparticles), especially in the field of machining difficult-to-cut materials such as titanium or nickel-based alloys.
- Advanced monitoring systems. The implementation of the industrial internet of things (IIOT) facilitates the development of monitoring systems that can apply machine learning or other artificial intelligent approaches to provide optimum machining performances. Under these systems, multi-objective optimization strategies that simultaneously consider diverse performance metrics, including surface roughness, energy consumption, tool wear, and environmental impact, can be deployed.

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