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Sustainable Machining: Tool Life Criterion Based on Work Surface Quality

Asif Iqbal [1,*], Guolong Zhao [2], Quentin Cheok [1], Ning He [2] and Malik M. Nauman [1]

[1] Faculty of Integrated Technologies, Universiti Brunei Darussalam, Jalan Tungku Link, Gadong, Bandar Seri Begawan BE1410, Brunei; quentin.cheok@ubd.edu.bn (Q.C.); malik.nauman@ubd.edu.bn (M.M.N.)
[2] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, 29-Yu Dao Street, Nanjing 210016, China; zhaogl@nuaa.edu.cn (G.Z.); drnhe@nuaa.edu.cn (N.H.)
* Correspondence: asif.asifiqbal@gmail.com; Tel.: +673-8929497

Abstract: Extending the use of a component without compromising its intended functionality is the neatest approach to enhance sustainability. From this perspective, limiting the working life of a cutting tool based merely on the blunting of its cutting edge to a specific value is highly questionable. The very question that serves as the motivation for this work is, "why should tool life criterion be based on the shape of the tool when all that matters for business is the quality of the part being machined?". This work puts forward a tool life criterion based on the surface quality of the machined part. The proof of the concept is provided by a series of face-turning experiments performed on a commonly used alloy steel using the following cutting inserts in dry conditions: (1) uncoated carbide; (2) coated carbide; and (3) cubic boron nitride (CBN). It is found that different combinations of tooling and cutting parameters lead to entirely different values of surface roughness at the same level of flank wear, thus raising the possibility of extending the working life of the tools. Overall, the CBN inserts yielded the longest tool life values, especially at high levels of cutting speed. Being more economical in respect of acquisition cost than the CBN inserts and more effective than the uncoated carbide inserts regarding tool life, the coated carbide inserts came out as the most sustainable tooling option. Finally, it is concluded that a tool life criterion based on work surface roughness can yield longer tool life values and make the machining process more sustainable. For the experimental work reported herein, the surface-quality based tool life criterion yielded on average 23% longer tool life. The presented work is novel as it presents a new approach to extend the working life of cutting tools without compromising the other sustainability measures. The outcomes are expected to find applicability in all sectors of the metal cutting industry, which are striving for elongations in tool life and improvements in work surface quality.

Keywords: economic sustainability; tool wear; sustainable machining; cutting speed; feed rate; process cost; cubic boron nitride; tungsten carbide

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1. Introduction

One of the modern-day quests is how to bring sustainability to the forefront of manufacturing. For the last two decades, researchers have been working on the issues concerning economic and environmental dimensions of manufacturing sustainability, such as reduction in specific energy consumption, conservation of work material, elimination of cutting fluids, and improvement in process productivity. From the perspective of material removal processes, enhancement in tool life is also an important sustainability measure and as such has received a matching level of consideration from the research community. In this regard, almost all the research efforts have focused on the technical aspects of the measure. In other words, the researchers have mostly concentrated on fine-tuning machining parameters such as cutting speed, feed rate, depth of cut, and cutting fluids to prolong the tool life against a given criterion [1]. What the current work is going to emphasize is that there is another facet of the measure to be looked upon. This facet of the sustainability measure is the criterion that governs the tool life. The possibility analyzed in this work is that replacing the tool life criterion based solely on the instantaneous shape of the tool's cutting edge with one based instead on the prevailing quality level of the machined surface might lead to elongation in tool life and, consequently, to enhancement in machining sustainability.

Traditionally, the working life of a machining tool is set to the attainment of a pre-decided magnitude of its flank wear (progressive mechanical damage of the tool's flank face) [2]. Other tool damage modes such as chipping, adhesion, and diffusion wear are rarely used in setting a tool life criterion because of the inherent difficulty in quantifying their magnitudes [3,4]. The cutting tool is expected to keep on machining until the life criterion, based on the evolved shape of its cutting edge, is met. At this point, the tool is considered to have "worn-out" and is deemed inappropriate for further cutting, irrespective of the quality of the machined surface it was yielding. Such a disposition takes a toll on the process's sustainability as the tool could still be further used under the condition of an acceptable work surface quality. It seems illogical to incur a tool replacement cost based on the condition of the resource (the tool) and not on that of the product (the workpiece being machined). Clearly, it is the quality of the product and not of the tool that is supposed to fetch the market share or the revenue. Moreover, this also has environmental implications. Extended use of a cutting tool delays its landfilling/recycling and reduces the rate of virgin material extraction that is required for the tool replacement. A brief review of the published literature in this regard is provided henceforth.

Throughout the decades, a specific value with respect to the width of the tool's flank wear land has been used as the tool life criterion [5]. Less frequently, some researchers have advocated using the depth of craters formed on the rake face due to sliding of the outgoing chip [6]. As the flank wear negatively affects the work surface quality, rake wear causes a reduction in the structural strength of the cutting edge [7]. With the advancements in cutting tool materials that thereby enhance the tool's strength, the call for using rake wear in the tool life criterion kept fading away. It was found that the tool life criterion has a profound effect on machining sustainability [2]. A lenient tool life criterion (a high value of flank wear) is favorable for reducing production cost, whereas a stringent criterion (a low value of flank wear) favors the metrics of work surface quality and specific energy consumption. A study focuses on finding the correlation between tool wear and work surface roughness in the milling of a titanium alloy [8]. The authors, from their experimental data, have concluded that tool wear was the predominant factor affecting the variation in work surface roughness. A relationship between tool wear and work surface roughness is worked out for turning a high-strength low alloy steel using tungsten carbide inserts [9]. It is found that the ceramic coated and uncoated carbide inserts, at the same levels of tool wear, yielded very different values of surface roughness during their late steady-state wear stage and failure wear stage. Jafarian et al. have used a search heuristic to find out the ideal tool life–in terms of machining time–for minimizing work surface roughness in the turning of a nickel-based superalloy [10]. The method suggested different tool life values suitable for the different combinations of cutting parameters. Based on a strong correlation between work surface roughness and tool wear state, an artificial neuro-fuzzy inference system is used to manage the tool life in an unmanned machining system [11].

Based on an experimental study carried out on high-speed milling of a hardened steel, Iqbal et al. have found that the work surface roughness is significantly influenced by the following four parameters, arranged in decreasing order of significance: tool's flank wear, cutting speed, feed rate, and depth of cut [12]. In another investigation, the cutting parameters–especially cutting speed and feed rate–are found to have significant effects on both tool wear and work surface roughness [13]. Sun et al. have argued that machining tools are mostly underused, resulting in a huge resource waste [14]. The authors have presented a 'remaining tool life prediction model' based on tool wear data, resulting in significant enhancements in tool life under various machining conditions. An energy (total amount of energy that is used directly and indirectly to deliver a product or a service)-based sustainability assessment approach is provided to quantify and improve the energy and resource efficiency of the machining system [15]. The authors have claimed that the approach has encompassed all the major aspects of machining sustainability such as energy consumption, material consumption, service consumption, and generated waste. Lv et al. have established energy efficiency, carbon efficiency, and green degree models with respect to the five kinds of metal cutting machine tools: turning, milling, grinding, planning, and drilling [16]. Following the models, the authors have suggested measures for energy conservation and emission reduction for these machine tools. Shin et al. have applied the concept of self-learning factories in a manufacturing domain to have accurate estimates of energy consumption while planning machining processes [17]. The approach seeks the minimum energy-consuming machine tool through accurate energy predictions, and thus leads to significant energy savings. Mamalis et al. have emphasized that the careful setting of cutting parameters is very crucial for achieving a long tool life and high productivity in extreme machining of ultra-hard alloy steels using cubic boron nitride (CBN) tooling [18]. The performances, in terms of tool life and work surface quality, of CBN and coated carbide inserts are mutually compared in continuous and interrupted machining of hardened steels [19]. The authors have reported that the CBN inserts yielded longer tool life only at the high levels of cutting speed. On the other hand, both kinds of inserts yielded comparable work surface integrity. Another study has focused on the aspects of tool life and work surface integrity in turning a nickel-based superalloy using coated carbide inserts [20]. The authors applied the maximum flank wear criterion of 0.2 mm and observed extremely steep curves of Taylor's tool life equation. An experimental investigation is carried out to find a compromise between tool life, work surface roughness, and productivity in turning a hardened steel using alumina-based ceramic inserts [21]. The authors have found that the simultaneous achievement of the three objectives was attained at the following settings of the cutting parameters: cutting speed 200 m/min; feed rate 0.08 mm/r; and depth of cut 0.3 mm. Likewise, another study has used fuzzy modeling to find a trade-off between tool life, productivity, and specific energy consumption in sustainable machining of a high-strength low alloy steel [22]. It is reported that the requirements of a long tool life are contrary to those of a high material removal rate (productivity) and low specific energy consumption. Rajemi et al. have presented a model to optimize the tool life in turning a high-carbon steel bar using carbide inserts under the constraint of a maximum ecological footprint [23]. Based on the optimization results, the authors have suggested performing machining at a low value of cutting speed to extract more value out of a high-cost high-energy tool. Recently, an experimental study has put forward a holistic analysis of tool life, productivity, and process cost in turning a titanium alloy using coated carbide inserts under wet and cryogenic cooling conditions [24]. The authors have concluded that the application of a more effective coolant (a cryogenic fluid) can cause a simultaneous achievement of opposing objectives, such as elongation of tool life, enhancement in productivity, and reduction in work surface roughness. Lastly, the International Organization for Standardization (ISO) has set the levels of tool wear as end-of-life criteria for various tool-work material combinations. ISO 3685:1993 is the relevant tool life testing standard for single point turning tools [25].

The literature review suggests that the improvements in tool life have mostly been sought through optimization of the cutting parameters and the introduction of efficient coolants while maintaining the conventional approach of deciding on the tool life. It is believed that a cutting tool may still possess the capacity to machine beyond the maximum allowable tool wear limit if it does not adversely affect the product quality. As such, the metal cutting industry is laying a heavy burden on the environmental and economic dimensions of sustainability. The current work capitalizes on this gap and presents an experimental study carried out on the turning of a commonly used alloy steel using carbide (uncoated and coated) and CBN inserts under the approach of terminating the tool's service only at the attainment of threshold values of work surface roughness.

2. Materials and Methods

This section describes the predictors, responses, work material, tooling, measurements, machine tool, and fixed parameters.

2.1. Predictors

Following predictor variables are controlled in the experiments:

1. Tool material. The following three kinds of turning inserts are used: (a) uncoated tungsten carbide; (b) ceramic-coated tungsten carbide; and (c) cubic boron nitride (CBN).
2. Cutting speed (V_c). The following two levels of the cutting parameter are tested: 150 m/min and 275 m/min. The two levels of V_c represent the average cutting speeds maintained during the runs. The maximum and the minimum cutting speeds at the outer diameter (100 mm) and the inner diameter (25 mm) are 240 m/min and 60 m/min, respectively, for the low level of cutting speed and 440 m/min and 110 m/min, respectively, for the high level.
3. Feed rate (f). 0.08 mm/rev and 0.12 mm/rev are the two levels of this predictor employed in this investigation.

A full-factorial design of experiments yields a total of 12 (=3 × 2 × 2) experimental runs. A 2-level full-factorial design of experiments is good enough to not only isolate the individual effects of a predictor but also to quantify the effect of an interaction between two predictors on a response.

2.2. Responses

The following response variables are evaluated for each of the 12 experimental runs:

1. Tool life (*TL*) measured in terms of total volume (mm^3) of work material removed. To evaluate the *TL* for each run, the averaged arithmetic surface roughness (R_a) and the average width of flank wear land (*VB*) are measured at the various levels of volume of work material removed (*Vol*). The run is terminated as soon as a tool life criterion is met, and the *TL* is taken as the instantaneous value of *Vol*. The tool life criterion is explained in the next paragraph.
2. Process Cost (*PC*), evaluated in BND/dm^3 (Brunei dollars per cubic decimeter of the work material removed in the machining process). The *PC* is the summation of the tooling cost and the time-dependent cost. The details are provided in the upcoming paragraphs.
3. Material Removal Rate (*MRR*), evaluated in mm^3/sec. *MRR* is a measure of the process's productivity and represents the volume of work material removed per unit of time. Being a deterministic measure, *MRR* is usually calculated rather than measured.

As R_a is the most widely used metric for quantifying the work surface roughness in research on machining, the same is employed in this work for measuring the machined surface quality. The work surface roughness-dependent tool life criterion is stated as follows. The useful working life of a cutting tool (cutting edge) is said to be completed if, from the start of the run, a total of three, two, or one measurement(s) of R_a = 1.4 µm, 1.65 µm, or 1.85 µm, respectively, are recorded. The values of R_a selected in the criterion are based on the results of the preliminary and continuation experiments, which showed the *Vol*-R_a plots picking up very steeply beyond R_a = 1.4 to 1.75 µm, especially for the carbide tools. Such a marked onset of deterioration in surface quality is an indication of the completion of tool life. The tool life criterion is based on the severity–frequency-based norm of risk assessment in terms of poor outgoing work quality. A severe deviation from the acceptable surface roughness limit should be allowed a fewer number of recurrences. Likewise, a milder deviation deserves more chances. Interpolation is applied to the last 2 passes of a run to determine the near-exact value of the *TL*.

As described above, *PC* is evaluated by adding up the tooling cost and the time-dependent cost for each run. The former is the acquisition cost of the tool's cutting edge, which is used for one experimental run until the tool life criterion is met. The latter is the summation of the machine operator's cost, electricity consumption (direct and overhead) cost, and the machine tool's depreciation cost incurred during the actual time period of the experimental run. The straight-line depreciation method is applied using a useful life of the lathe as 10 years. Table 1 provides the costing details. As a currency-based absolute value of cost keeps on changing with time, it is worthwhile to use a 100-scale comparative costing approach in order to have more realistic and comprehensible comparative *PC* values across the runs. In such an approach, the highest and the lowest *PC* values are set to 100 and 0, respectively, whereas the other 10 values are calculated using linear interpolation between the two extreme values.

Table 1. Purchase/consumption cost of various items related to a turning process.

S/No.	Item	Category	Cost	Remarks
1	Uncoated carbide insert	Tooling	9.15 BND	Three cutting edges per insert
2	Coated carbide insert	Tooling	12 BND	Three cutting edges per insert
3	CBN insert	Tooling	41.5 BND	Three cutting edges per insert
4	Machine operator	Time-dependent	1500 BND/month	22 eight-hour-long working shifts in a month
5	Machine tool	Time-dependent	280,000 BND	Salvage value = 10,000 BND
6	Electricity tariff	Time-dependent	0.23 BND/kWh	Machine tool power = 1500 W; HVAC/Lighting power = 1200 W

Finally, the average value of *MRR* is calculated using the following analytical relationship for face-turning:

$$MRR_{avg} = \pi f a_p N(D_o + D_i)/2 \quad (1)$$

where f, a_p, N, D_o, and D_i represent the feed rate, axial depth of cut, work rod's rotational frequency, rod's outer diameter, and rod's inner diameter, respectively. Based on the variations in f and N, four distinct values of *MRR* are possible, which are presented in Table 2.

Table 2. The average material removal rates for the four cutting speed–feed rate combinations used in the experiments.

S/No.	V_c (m/min)	N (r/min)	f (mm/r)	V_f (mm/min) *	MRR (mm^3/s)
1	150	763.9	0.08	61.1	99.6
2	275	1400.6	0.08	112	182.6
3	150	763.9	0.12	91.7	149.4
4	275	1400.6	0.12	168.1	273.9

* V_f is the feed speed evaluated for the given combination of N and f.

2.3. Work Material and Tooling

The work material used in the study is a high-strength low alloy steel, AISI 4340. It is a heat-treatable alloy that contains chromium, molybdenum, and nickel as the main alloying constituents besides iron and carbon. Its high toughness and strength in a heat-treated condition make it a very popular material for the manufacturing industry. In this work, the material is used in the form of solid rods with diameters and lengths equal to 100 mm and 150 mm, respectively. The rods are heat-treated (heated at 835 °C, soaked for 45 min, quenched in oil, and tempered at 545 °C) to obtain the ultimate tensile strength, yield strength, surface hardness, and elongation of 1205 MPa, 1140 MPa, 38 HRc, and 14.5%, respectively.

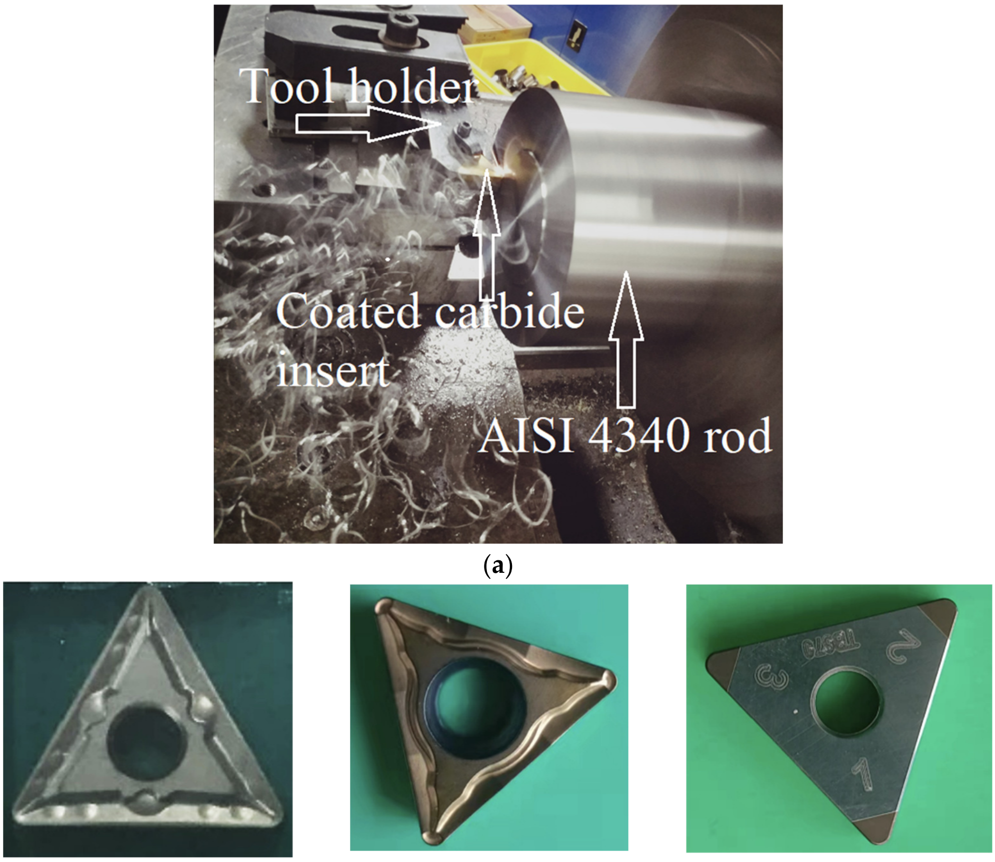
The following turning inserts are used in the experiments: (a) uncoated tungsten carbide: TNMG 160408 ML K10; (b) coated tungsten carbide: TNMG 160408 ML TT5080; and (c) cubic boron nitride: TNMA 160408 LS3 TB670. Each of these inserts has three cutting edges, and therefore the insert's purchase cost is divided equally over three runs. The cutting insert (b) is coated with multiple layers of TiN and TiAlN using physical vapor deposition. All three types are 60° negative triangular inserts (0° clearance angle), which possess a corner radius of 0.8 mm and are fitted on the tool holder WTJNR 2020 2525 M16, thereby providing the approach and rake angles of 93° and −10°, respectively. All the tooling (inserts plus holder) is acquired from TaeguTech® Ltd., Daegu, Korea.

2.4. Measurements

An optical microscope, ARTCAM 130-MT-WOM, is used to measure the average flank wear (*VB*) of the used cutting inserts. The width of the flank wear land is measured at four distinct locations of the cutting edge. The equally distanced four measurement locations are selected in this way to uniformly cover the whole wear land on the flank face adjacent to the cutting edge. The *VB* is then evaluated by taking the mean of the four measurements. R_a, on the machined work surface, is measured using Mahr surface roughness meter, MarSurf M 300 C. The measurements (in radial as well as hoop directions) are taken at the radii of 20, 27.5, 35, and 42.5 mm. The sampling length for each measurement is 4 mm. The R_a is then evaluated by taking an average of the eight readings.

2.5. Machine Tool and Fixed Parameters

All the experimental runs are carried out on a precision automatic horizontal lathe, Weida CA 6140, possessing the main motor power of 7.5 kW, a maximum rotational speed of 1500 rpm, and a maximum feed speed of 2 m/min. The maximum work length and diameter of 0.9 m and 0.4 m, respectively, can be turned on the machine tool. Figure 1 presents the experimental setup and the images of the three cutting inserts used in this study. All the runs are conducted in a dry condition. It is also ensured, for all the runs, that the protruded length of the work rod beyond the chuck jaws remains between 80 mm and 120 mm to offset any effect of protrusion-induced vibrations on surface roughness. The face-turning is performed by feeding the cutting insert radially inward from the outer diameter (100 mm) up to a stopping point where the diameter is exactly 25 mm. An axial depth of cut of 0.5 mm is ensured for all passes of all the runs. Based on D_o = 100 mm, D_i = 25 mm, and a_p = 0.5 mm, a volume of 3681.5 mm^3 is removed from the face of the rod in a single face-turning pass of a run. Therefore, it can be supposed that if the tool life criterion is achieved in exactly seven passes of a run, the tool life for that run would be exactly 25,771 mm^3. Furthermore, as each of the three kinds of inserts used in the experiments has three cutting edges, it can serve three experimental runs. Inherent to the face-turning process, the cutting speed gradually decreases as the cutting tool feeds inward, which may cause an effect on the surface roughness. The effect is offset by ensuring that the roughness measurement points are uniformly located between the cut's starting point (D_o = 100 mm) and ending point (D_i = 25 mm), as detailed in Section 2.4. Moreover, strict uniformity across the runs concerning the cutting parameters and the measurement procedure is also ensured.



(a) (b) (c) (d)

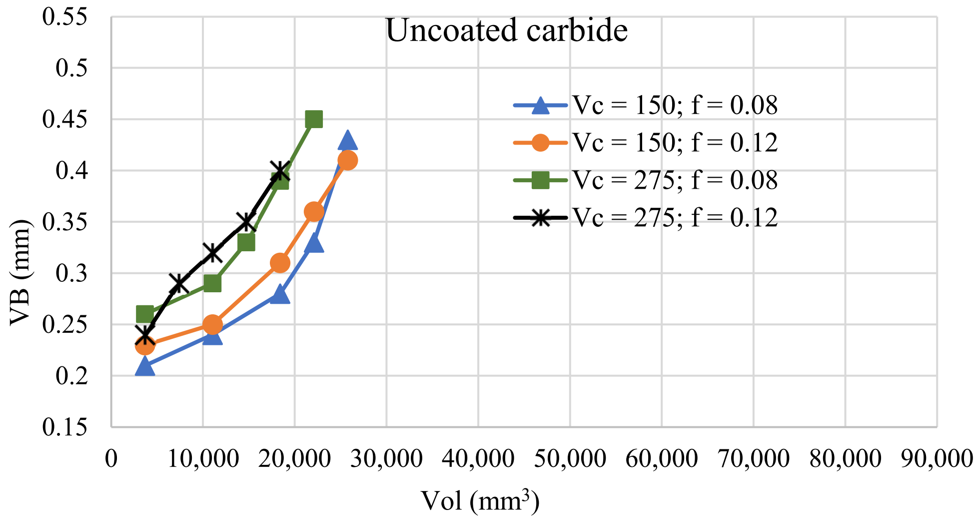
Figure 1. Experimental setup: (**a**) the lathe, tool, and the work material; (**b**) the uncoated carbide insert; (**c**) the coated carbide insert; and (**d**) the cubic boron nitride (CBN) insert.

3. Results

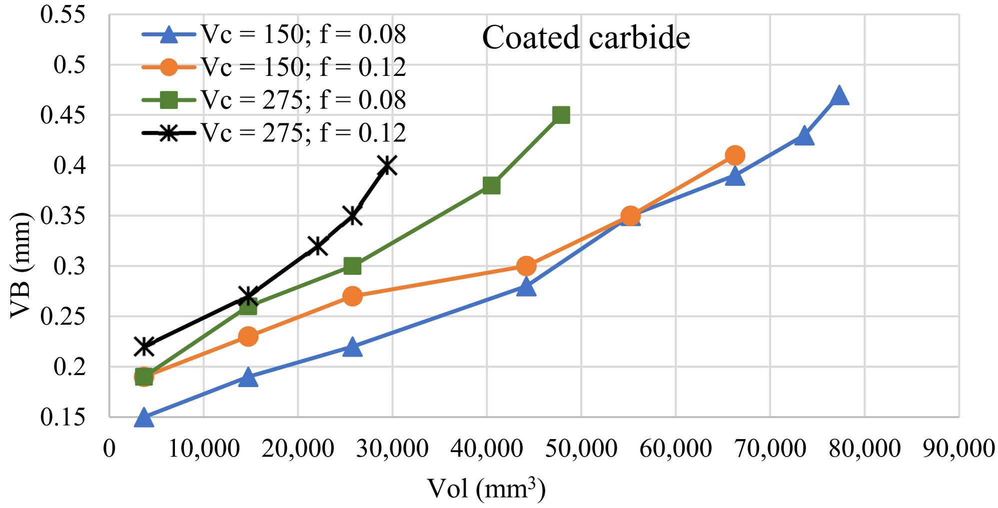
This section provides the experimental results regarding tool wear, work surface roughness, tool life, and process cost.

3.1. Progressive Tool Wear and Work Surface Roughness

Figure 2 presents the progress of the cutting edge's flank wear with the volume of work material removed for the three kinds of cutting inserts used in the experiments. Equal scales on the ordinates and abscissas are used to have a true comparison between the performances of the cutting inserts. The three plots show the steady progress of tool wear, but at different slopes. The gain in the progressive wear is steepest in the case of the uncoated carbide inserts, yielding the shortest tool life values. The results in respect of the other two are comparable, with the high level of cutting speed giving a clear edge to the CBN insert with respect to long tool life. Nevertheless, their individual performances are far superior to that of the uncoated carbide insert. On average, the increased level of cutting speed has caused 23%, 47%, and 3% reductions in the volume of material removed by the uncoated carbide, coated carbide, and CBN inserts, respectively. This suggests that the carbide-based tooling is much more vulnerable, with respect of tool damage, to an increase in cutting speed than the CBN-based tooling.



(**a**)



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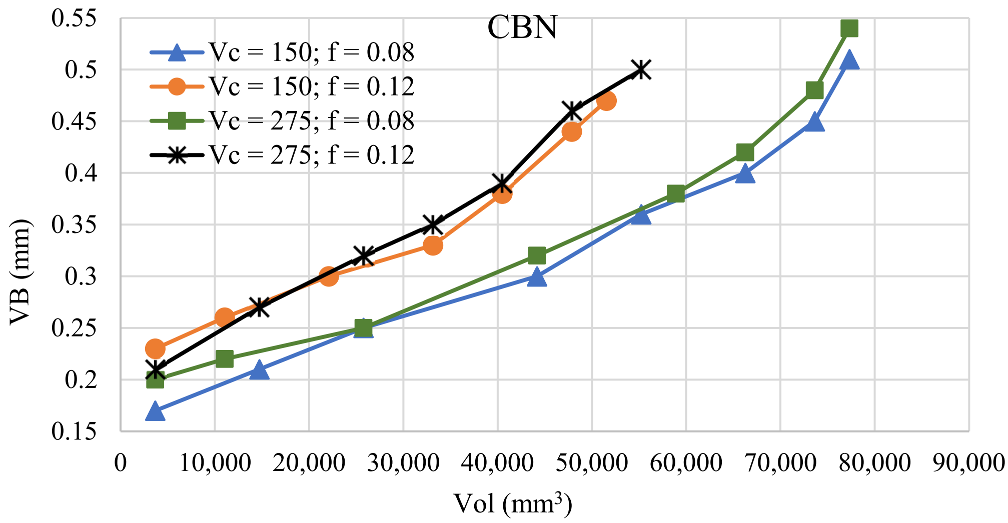
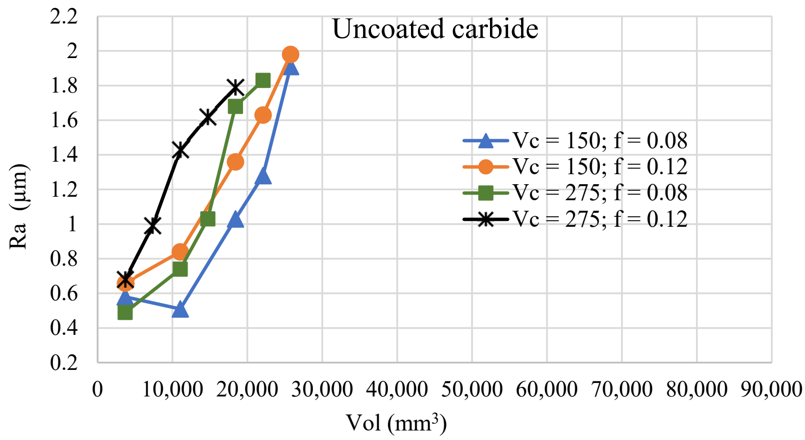


(**c**)

Figure 2. Progress of tool's flank wear with volume of work material removed, categorized with respect to the three cutting inserts used in the experiments: (**a**) uncoated carbide; (**b**) coated carbide; and (**c**) CBN. V_c and f are represented in m/min and mm/rev, respectively.

The plots for the carbide inserts (uncoated and coated) show that the effect of cutting speed is significant and more potent than that of feed rate. A high level of cutting speed drastically increases the tool wear rate and thus leads to a mammoth cut in the tool life. Higher cutting speeds are accompanied by higher cutting temperatures, leading to softening of the tool material and lessening in wear resistance [26,27]. For the same inserts, the high level of feed rate, due to a resulting increase in chip load, has also accelerated the tool wear, but at a lower rate than that created by the cutting speed. The CBN inserts have achieved quite a different result. The effect of feed rate in accelerating flank wear is more compelling for CBN than it is for the other two kinds of inserts. This is evident by looking at the wide gap between the orange/black and blue/green curves of the third plot. CBN inserts/tips are known to experience elevated wear rates at high feed rates in continuous machining of hard steels [28]. On the contrary, the effect of cutting speed on tool wear is almost negligible. The observation stands in support of the already established high temperature-dependent wear resistance of the artificially produced ceramic material (CBN) [29].

Figure 3 presents the progress of R_a with the volume of work material removed. The three R_a plots reflect the respective *VB* plots (Figure 2) without the first 3–4 passes (one pass represents 3681.5 mm^3 of work material removed). This suggests that the work surface roughness is greatly dependent on the tool wear state during the middle and the final stages of the tool life. Moreover, the Pearson correlation coefficient between the *VB* and R_a data (Figures 2 and 3) is found to be 0.887, suggesting a strong positive relationship between the two measures. As the tool wear is very small during the initial stage of tool life, the work surface roughness finds its dependence on the other process parameters, including cutting speed and feed rate.



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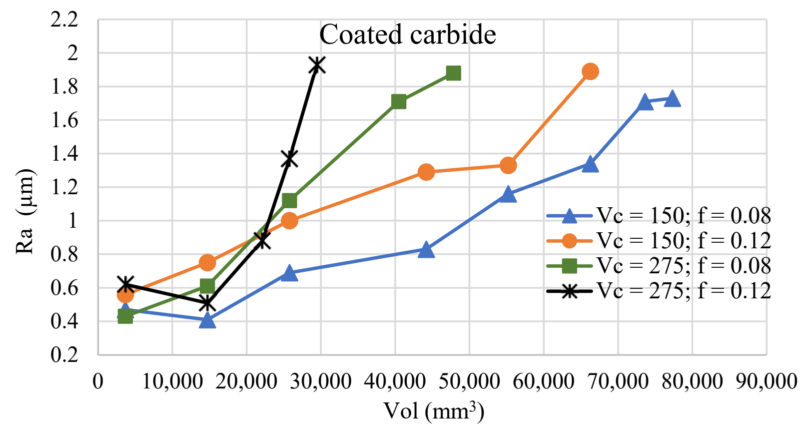
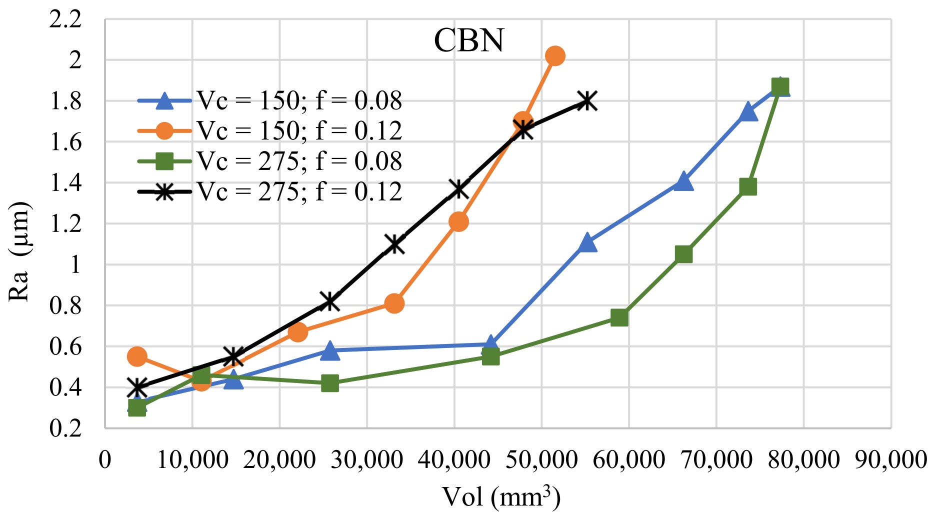


(**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. Progress of average arithmetic surface roughness with volume of work material removed, categorized with respect to the three cutting inserts used in the experiments: (**a**) uncoated carbide; (**b**) coated carbide; and (**c**) CBN. V_c and f are represented in m/min and mm/rev, respectively.

The three plots of Figure 3 show a steady rise in R_a with the volume of material removed. A decline in a R_a curve, if any, is only observed during the first four passes of the face-turning process. This is the stage where the *VB* is small and does not pose any significant effect on the surface roughness, thus, R_a can show signs of improvement under the effects of the tooling and cutting parameters. The individual slopes of the curves depend massively on the kind of cutting insert and, to lesser extents, on the two cutting parameters. The unacceptably "high" levels of R_a (in excess of 1.7 µm) are attained much more quickly by the uncoated carbide inserts as compared to the other two. The attributed reason is that the high wear rates experienced by the uncoated inserts deprive them of the ability to keep them cutting with an acceptable level of surface quality up to high values of *Vol*. This is why the R_a curves of the uncoated carbide inserts are much steeper than those of the other two tools. Although there is no significant difference between the general performances of the coated carbide and CBN inserts, the former outperformed the latter in respect of only one of the four runs (V_c = 150 m/min; f = 0.12 mm/rev). Thus, it can be safely stated that the CBN inserts have yielded better work surface quality than the tungsten carbide inserts (coated and uncoated). The higher hardness of CBN is to be credited in this regard. For the CBN inserts, the two runs carried out at the low level of feed rate have yielded significantly lower surface roughness than the other two runs. On the other hand, the carbide inserts have yielded significantly lower R_a values at the low level of cutting speed, especially at the later stages of the runs.

A nano-scale coating of a ceramic material over the tungsten carbide substrate is known to resist tool wear, mainly due to the increased surface hardness of the tool. The ceramic coating materials–TiN and TiAlN, exceedingly harder than tungsten carbide–have not been successful as tool substrates because of their very low toughness values. Nevertheless, having a tough substrate such as tungsten carbide, the ceramics can be used as layers coated upon the substrate to produce a very hard and acceptably tough machining tool. The resulting combination (a coated carbide tool) can yield comparable results with respect to an exceptional tool material–such as CBN–in terms of tool wear under certain machining conditions, as is seen in Figure 2b,c. Ceramic coatings are also found to reduce tool damage by lessening the frictional effects at the tool-chip interface and the resulting thermal wear [30].

3.2. Tool Life

Figure 4 presents the results regarding the tool life of the 12 runs. Clearly, the uncoated carbide inserts have performed very poorly in this regard. In general, the longest tool life values, following the work surface roughness-based criterion, are yielded by the CBN inserts. The clear superiority of the coated carbide inserts over the CBN inserts is visible in a solitary run–the one carried out at the low and high levels of cutting speed and feed rate, respectively. On the other hand, the CBN inserts have shown strong dominance over the coated carbide inserts in the runs executed at the 'high' level of cutting speed. Since cubic boron nitride possesses significantly better refractory properties than tungsten carbide, the increased working temperature due to the increased level of cutting speed does not deteriorate the cutting edge of a CBN insert as much as it does to the coated carbide insert [31].

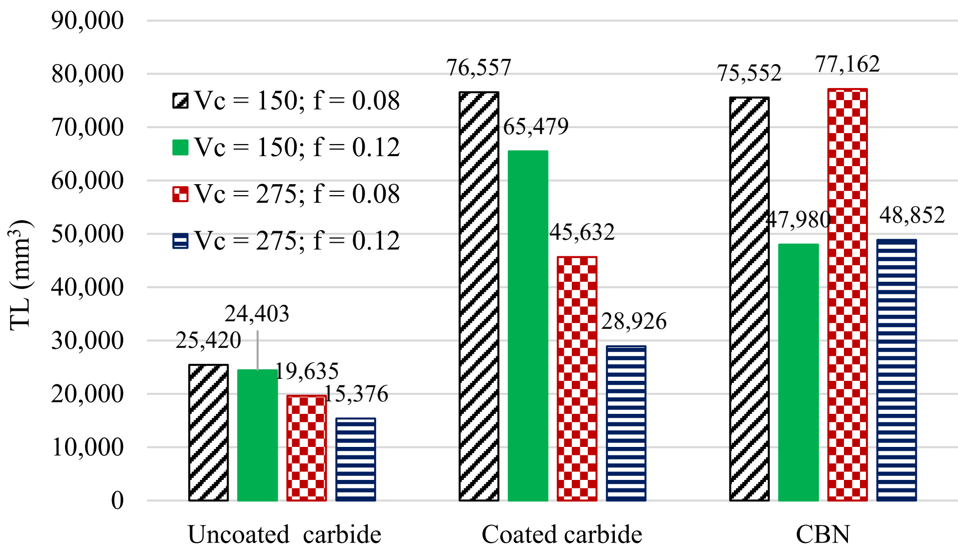


Figure 4. Tool life values for the 12 experimental runs.

By mutually comparing the last two plots of Figure 2, it can be found that the CBN and coated carbide inserts have crossed the "VB = 0.5 mm" mark on three and none of the four occasions, respectively. This happened because the CBN inserts were found to incur significantly lower values of R_a at the same values of VB, V_c, and f. This observation has contributed to the longer tool life values of the CBN inserts in comparison to the coated carbide inserts. A harder substrate, as in the case of CBN, has led to better surface quality even at the same levels of tool wear and the two cutting parameters. It is already well established that a harder tool material yields a better work surface finish due to lower elastic deformations under varying tool stresses [32].

It is interesting to note from Figure 4 that the carbide inserts (uncoated and coated) are withered by the increases in cutting speed and feed rate whereas the CBN inserts are immune to the effects of the increase in cutting speed but not to the feed rate. The vertical bars related to CBN suggest no loss in tool life due to the increase in cutting speed. On the other hand, they experience about a 36% drop in tool life by increasing the feed rate from 0.08 to 0.12 mm/rev, irrespective of the employed level of cutting speed. In a nutshell, the analysis of the experimental results on R_a suggests that the CBN inserts yield the longest tool life values of the three inserts tested in the study. To assure the stated outcome, the CBN inserts need to be operated at a low level of feed rate.

3.3. Process Cost and Productivity

Figure 5 presents the 100-scale comparative process costs with respect to the 12 runs. Clearly, the coated carbide inserts outperform the others on this front. The CBN inserts have turned up to be the most expensive option, mainly due to their extraordinarily high purchase cost. On the other hand, the uncoated carbide inserts do not appear to be an economical option either due to the high wear rates and the resulting exceedingly short tool life values. The effect of tooling on the *PC* is so massive that the most economical run of the most expensive option (CBN) is more expensive than the most expensive run of the most economical option (coated carbide). Such a strong impact of the tool acquisition cost on the *PC* is conceivable from the fact that it holds, on average, a 79.6% share in the total process cost.

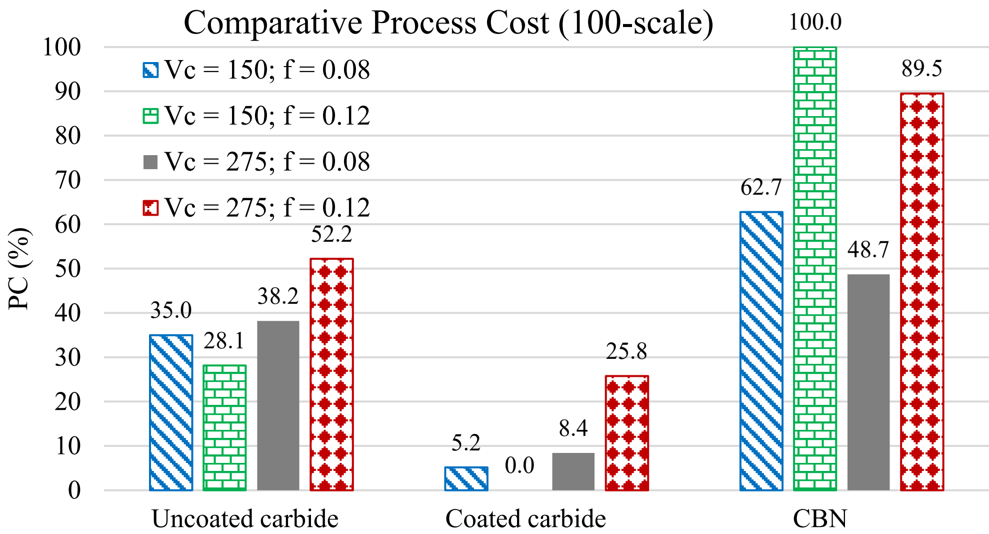


Figure 5. Process cost for the 12 experimental runs.

Productivity, represented by material removal rate in this work, depends on the levels of the cutting parameters (cutting speed and feed rate) only. As presented in Table 2, the MRRs associated with the high (H) and low (L) levels of V_c and f can be arranged in the following order of their descending magnitudes (V_c, f): (H, H); (H, L); (L, H); and (L, L). Taking the lowest level of MRR (99.6 mm^3/s) equal to 1, the comparative MRR levels, in the same order, can be written as follows: 2.75; 1.83; 1.5; and 1. Thus, the range of the cutting parameters controlled in the experiments yields a 175% increase in productivity from the lowest level of MRR to the highest.

Figure 5 suggests that for the carbide inserts (uncoated and coated), the lowest process cost is associated with the second-lowest level (1.5) of MRR. For the CBN inserts, the lowest PC is associated with the second-highest level (1.83) of MRR. This observation suggests that the two sustainability measures–process cost and productivity–do not find each other in a mutually harmonious state for the sake of improving machining sustainability. The two, therefore, would face a compromising situation with respect to the sustainability objective.

4. Discussion

The severe climate changes the world is currently facing and the ongoing depletion of materials from the earth's crust are forcing the manufacturing industry to run its resources for longer against the same levels of production output. From the perspective of manufacturing processes, this requirement translates into the objective of increasing production per tool without reducing productivity. Extended use of a tool not only supports material conservation by delaying/reducing virgin material extraction, but also conserves energy by averting the requirement of processing virgin material or recycling the end-of-life tooling. The current work contributes to this objective by presenting a sustainable way of increasing tool life without compromising productivity or work quality.

The prime objective of a manufacturing entity is to make products with acceptable quality and at a minimum possible cost. In other words, the cost of production needs to be minimized while keeping the product quality above a limiting value. As the tool acquisition cost holds around a staggering 80% share of the total processing cost (discussed in Section 3.3), it is critical to run the tool for as long as the quality specification permits. Worksurface roughness is one of the most important quality characteristics taken care of in the machining domain. This work advocates judging tool life against the requirement of work surface roughness rather than against a pre-decided level of flank wear, which causes a premature curtailment of the tool's service.

Table 3 presents the tool life and the flank wear at the attainment of the tool life criterion for the 12 runs. The *VB* at tool life attainment varies from a minimum of 0.359 mm to a maximum of 0.538 mm, suggesting a difference of about 50%. A lion's share of the published work on tool life and tool wear has reported *VB* = 0.3 mm as the tool life criterion. Let us take *VB* = 0.359 mm (the minimum value in this work) as the conventional tool life criterion, which is still much bigger than the one generally used (0.3 mm). Enforcing this criterion means that all the other 11 runs would have been stopped when their respective *VB*s had reached 0.359 mm. Such an approach would have yielded, on average, 23% shorter tool life values for the 11 runs. Therefore, it can be safely stated that the tool life criterion based on the work surface quality has caused the cutting tools to run 23% longer. On an industrial scale, such a gain would yield a massive contribution toward the economic and environmental aspects of manufacturing sustainability.

Table 3. *TL* and *VB* at the completion of tool life.

V_c (m/min)	f (mm/rev)	**Uncoated Carbide Inserts**		**Coated Carbide Inserts**		**CBN Inserts**	
		***TL* (mm^3)**	***VB* (mm)**	***TL* (mm^3)**	***VB* (mm)**	***TL* (mm^3)**	***VB* (mm)**
150	0.08	25,420	0.42	76,557	0.462	75,552	0.481
150	0.12	24,403	0.391	65,479	0.406	47,980	0.442
275	0.08	19,635	0.41	45,632	0.429	77,162	0.538
275	0.12	15,376	0.359	28,926	0.393	48,852	0.468

With a focus on the economic dimension of sustainability, coated tungsten carbide inserts are a clear choice for tooling with respect to turning an alloy steel. Unfortunately, the combination of the cutting speed (150 m/min) and the feed rate (0.12 mm/rev) at which this insert incurs the lowest process cost yields the second-lowest level of productivity (MRR = 149.4 mm^3/s). CBN inserts, on the other hand, yield very good tool life values at higher levels of productivity but, unfortunately, even the most economical run (PC = 48.7%) with a CBN insert is too costly. Lastly, the uncoated carbide inserts are nowhere near the performance of the coated counterparts. Thus, from a holistic perspective, coated carbide inserts should be used for the continuous machining of an alloy steel. Moreover, the process should be carried out at a medium-to-high level of feed rate and the level of cutting speed that favors the desired inclination on the cost-productivity spectrum.

From the perspective of the environmental dimension of sustainability, both CBN and coated carbide have their own merits whereas uncoated carbide should clearly be ruled out. As the CBN inserts have yielded the longest tool life values, they are supposed to be the most environment-friendly choice because they keep the end-of-life activities (recycling, remanufacture, landfilling, etc.) at bay for a longer period. On the other hand, although the coated tungsten carbide inserts yield slightly shorter tool life values, the availability of their major ingredient (tungsten) on the planet is not as limited as boron nitride is. As such, both tools sit on an equal footing in terms of environmental sustainability.

The presented work is novel in the sense that it puts forward a new and more logical approach for deciding on the working life of a metal cutting tool. The approach is objective as it relies on one of the features of the product (work surface quality) rather than the existing condition of the tool. The techniques adopted by the previous studies (a few of them reviewed in the opening section) have been subjective as their tool life decisions are based on the wear condition of the tools. Such techniques are likely to yield less-than-full-capacity usage of the tools, because they could be used for a longer period of time while still meeting production requirements in most machining conditions. The works presented by Zhang et al. [8] and Sun et al. [14] have been distinct and tradition-breaking in this regard. The former has advocated the amalgamation of the tool's flank wear and work surface conditions in deciding the tool life in the milling of a titanium alloy, whereas the latter has presented an optimization approach to extend the remaining useful life of a tool by fine-tuning the cutting parameters in accordance with the existing wear condition of the tool and the work material to be cut.

Lastly, we wish to clarify that the objective of the article is to experimentally prove that a tool life criterion based on work surface roughness is more sustainable than when based on tool flank wear. Its objective is not to yield a technical model for estimating tool wear, tool life, or surface roughness based on the levels of cutting speed and feed rate selected and the choice of tool material. For a technical mapping of the cutting process, the generated data are not enough for the work material–tool combination covered in this work. As such, the results cannot be generalized for the other tool–material combinations. Nevertheless, as far as the conclusion regarding the superiority of the work surface roughness-based tool life criterion is concerned, it would hold true for most of the work material–tool combinations.

5. Conclusions

The article explores a concept that establishing tool life criterion on work surface quality rather than the cutting edge's flank wear would elongate the working life of a machining tool and, consequently, strengthen the environmental and economic dimensions of manufacturing sustainability. An experimental study is carried out regarding face-turning of a high strength low alloy steel using CBN and coated and uncoated carbide inserts. The experimental results are analyzed for tool life in terms of the volume of material removed prior to meeting the criteria based on averaged arithmetic surface roughness of the machined surface. Based on the analyses of the experimental results provided above and followed by the discussion, the following conclusive points can be drawn:

1. The critical finding of the work is that adoption of a worksurface roughness-based tool life criterion leads to prolonging the working life of a cutting tool without compromising the acceptable work quality or process's productivity. On average, a 23% elongation in tool life is recorded for the set of experiments presented in this study.
2. Using coated tungsten carbide inserts for machining an alloy steel is a much more sustainable option than using uncoated carbide inserts or CBN inserts. They run exceedingly longer than uncoated carbide inserts and are exceptionally more economical than CBN inserts. Nevertheless, even the coated carbide inserts start losing viability as the material removal rate (productivity) is increased.
3. CBN inserts respond firmly, in terms of tool damage, to an increase in cutting speed, but their procurement cost remains too high to justify the resulting gain in productivity.

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