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Sustainability Analysis of AISI 1018 Turning Operations under Surface Integrity Criteria

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Abstract: While the world is moving towards achieving sustainable development goals for responsible production and consumption, there is a need for metrics deployment for lower practical levels. From a manufacturing perspective, definitions of sustainability indicators are required for industrial processes and operations. These metrics encourage the evaluation of manufactured parts and whether they meet the quality requirements in both a qualitative and quantitative way. The present contribution proposes a framework for defining a structured set of metrics customizable for operations in different manufacturing technologies. In order to validate the proposal, an experimental data analysis of turning operations was completed and the surface integrity was defined as the control feature. The selected material was AISI 1018 and the main process parameters were controlled in order to identify their influence—not only in the final mechanical quality of the part, but also in the sustainability indicators. To achieve this goal, a set of experiments was performed wherein some of the fundamental machining parameter values were fixed, while other key parameters were modified. The results obtained helped to determine the criteria for predicting the quality of the turning operation when the effects are not readily evident in visual or dimensional inspections, as well as in evaluating the environmental impact that guarantees optimal part manufacturing.

Keywords: green manufacturing; turning operations; sustainability metrics; surface integrity; machining parameters optimization

1. Introduction

Improvement in machining operations is an important role in the life cycle of a product, mainly in the connection that must exist between the design and the finished components, since the time and cost of production can significantly affect the remaining phases of the process and life cycle of the product [1]. There are two relevant aspects that must be considered when machining a part, which must be defined and controlled in the process: surface finish and integrity of the surface. Surface finish refers to geometric irregularities, whereas surface integrity refers to the metallurgical alterations of the surface and the surface layer, which must be measured and maintained within the tolerances specified in the processing of any product [2].

Jawahir et al. [3] presented the progress of a study conducted by a CIRP (International Institution for Production Engineering Research) collaborative working group on the surface integrity and functional performance of components. They reported progress in experimental and theoretical investigations on the integrity of surfaces in the material removal processes. In the study of production systems for sustainable manufacturing, three main dimensions define the criterion of sustainability when modelling machining processes: economic, environmental and social dimensions [4]. Some works insist on considering them in earlier design phases as some of the principal expectations to improve the quality of the product [5]. In the case of the social dimension, it is starting to be evaluated with quantitative indicators. Recent research performed by Bhanot, Rao and Deshmukh [6] proposed a methodology and a calculation method to evaluate this dimension in machining processes, specifically for turning operations.

When analyzing the machining process, the selection of a machining center of the same technology is difficult [7], and the parameters and quality of the manufactured part must be considered. Recent research has proposed methodologies which quickly and simply assess manufacturing processes to determine their green performance [8]. Such research is not only complemented by considerations of the economic and environmental impact, but also in defining some study frameworks. In addition, they may focus on evaluating the coefficient of social impact in the organization [9].

A review of the state of the art evaluations of surface integrity through mechanical properties revealed an advanced development scenario in different experimental methods. The analysis of several works, such as those by Leskovar [10], Lalwani [11] and Sasahara [12], revealed that they keep the same research structure—the use of variable machining parameters to analyze changes in metallographic studies. Jayal et al. [13] discussed the recent trends in developing improved sustainability scoring methods for products and processes, as well as predictive models and optimization techniques for sustainable manufacturing processes, with a focus on dry, near-dry and cryogenic machining as examples.

Hence, the importance of studies on the influence of feed, speed and depth of cut at constant cutting speed on microhardness and microstructure is evident [14]. The industrial revolution was an effect of CNC (Computerized Numerical Control) machinery development [15] and allowed for the control of machining parameters in an automatic way. For that, this paper summarizes novel quality controls that can be implemented in the manufacture of pins and parts of machines that require a turning process.

Nagendra et al. [16] carried out a study which compared the workability and properties of AISI 1018 steel in austempering and annealing conditions. Their results showed that the austempering process increased the tensile strength and hardness of the steel, as well as its workability. Consequently, the austempering process will have a direct influence on the strength and hardness of parts.

Mohsan et al. [17], in their study of the difficult-to-machine Inconel 718 alloy in orthogonal turning, conducted an evaluation of dry and high-pressure jet-assisted machining (HPJAM). The machining parameters and coolant conditions were investigated to optimize surface integrity. Machining forces, microhardness, profile, and areal surface topography were analyzed. Their results showed that a higher cutting speed of 140 m/min and a coolant pressure of 150 to 200 bar were the optimum settings for producing a satisfactory machined surface.

Srivastava et al.'s work [18] included a survey of various research in which surface integrity was considered a primary phase of investigation in either conventional or non-conventional machining processes. Surface defects, such as crack initiation, surface scratching, brittle fracture of surface particles, recrystallization and phase transformation, plastic deformation and residual stresses, were found to be among the factors that affected machining characteristics. In addition, the suitable quantity surface finish, surface residual stresses, microhardness of the machined surface, and topographical and morphological aspects were also identified as key factors which may be used to judge the quality of machined surfaces.

Recent research on materials suggests machinability may be evaluated according to changes in the machining tools and cooling lubrication environments, while optimization of cutting conditions can be achieved using statistical methods such as Taguchi, as proposed by Hwang, Lee and Park [19]. The work of Bhanot, Rao and Deshmukh [6] presented a sustainability assessment framework for a turning process with respect to the manufactured product. This framework was developed for the automotive industry using empirical relations after conducting full tool wear criteria experiments.

Upon review of the literature, we found there was a break between the general sustainable manufacturing models and the particular manufacturing models. The general sustainable models did not present a deployment of devoted sustainable metrics within a general framework that could be matched in different manufacturing technologies. Our research objective was to define a general framework for sustainable manufacturing with all the inputs, resources, controls and outputs included, and to apply this framework progressively to manufacturing techniques. The purpose of this contribution is to describe how to apply our framework in a particular case and show its validation with a case study of a turning operation of AISI 1018.

The following sections begin with a description of the applied experimental methodology, with a brief description of the approach to a general sustainable manufacturing framework as part of the research method and the experimental procedure. After this, the experimental results of the collected data with respect to the selected metrics for the validation step are exhibited. Then, there is a discussion about the results and, finally, the conclusions and potential future work are presented.

2. Materials and Methods

2.1. Study Material and Applications

The contribution of this research work consists of the deployment of sustainable metrics for a manufacturing technology constructed from the general approach. This contribution is part of the assessment methodology for evaluating the sustainability of a manufacturing process. The machining of metals is one of the most extended processes within the manufacturing industry and thus a turning operation was selected for our application. Validation was performed on machined AISI 1018 steel material due to its extensive use in mechanical products.

Recent investigations into the effects of machining on surface integrity have been developed for different types of materials, which allows for behavior to be predicted at the microscopic level (depending on the cutting conditions applied in the process).

Yang et al. [20] presented a study on the surface integrity of titanium alloy following milling by micro-textured ball-end milling cutters. In this study, the influence of changes in the micro-texture parameters on the roughness and hardening of the surface was assessed.

Pan et al. [14] reviewed recent works on the evolution of microstructure in the context of machining components and concluded that the machined surface integrity—which was affected by the microstructure properties—covered residual stress, microhardness, roughness.

Lu et al. [21] studied induction assisted milling (IAM) on Inconel 718 with an AlTiN coated carbide tool and an uncoated carbide tool. On one hand, the work concluded that the surface roughness and tool wear indicated better quality with a coated tool as the spindle speed was increased. On the other hand, the uncoated tools had a lower machinability level due to higher thermal effects compared to the coated tools.

Gupta et al. [22] discussed the features of two innovative techniques for machining an Inconel 800 superalloy by plain turning, while also considering some critical parameters, such as the cutting force, average surface roughness (R_a), tool wear rate and chip morphology. Their research findings highlighted the robustness of the near-dry machining process over the dry machining routine, as well as demonstrating its great potential to resolve the heat transfer concerns associated with this manufacturing method.

Yue et al. [23] analyzed changes in part functionality induced by alterations in surface integrity in the metal milling process and concluded that reasonable selection of process parameters affected the machined surface integrity, thereby controlling the workpiece’s performance.

Although turning operations are one of the most investigated experimental works among all contributions to the literature, our proposal adds further data and was obtained from a novel case study developed within a methodological research model.

2.2. Research Method

The present research started with the definition of a sustainable manufacturing framework which considered all the required activities for completing all the product parts. The framework had a wide perception of the manufacturing environment and it considered the different processes, including activities, inputs and outputs.

For the research approach, specific machining environments were defined and, for this particular work, the sustainability model for turning machining technology was examined. The detailed model, which describes the activity process of turning with its inputs, outputs, controls and resources, is shown in Figure 1. All the materials and information flows must be analyzed under not only the technological criteria, but also from the sustainability point of view.

In this work, we will focus on the analysis of surface integrity. Material flows and other information will be analyzed in complementary studies that are beyond the present research scope but will be part of future publications.

- **Process inputs**: In this model, we considered remanufacturing as a possible entry in the machining process, taking into account the whole part life cycle. However, the main input in our work was a raw part that had not been previously manufactured.
- **Process resources**: In order to know exactly how the output was going to be obtained, all the involved resources had to be considered. For that reason, the proposed model included the tool and tooling resources as the first main group and, as a second main group, all the facilities, machines and human resources for the material processing activity.
- **Process controls**: The controls of the process allowed online or offline verification of the quality of the final part or the effective operation of the process. In manufacturing, controls can come from part drawings, manufacturing process plans, product requirements or customized metrics. For our research objective, we defined a series of metrics from the general scope to the detailed operation control. They included indicators from the technological perspective that could be linked to sustainable metrics. In some cases, controls were capable of considering economic and social features.
- **Process outputs**: The output was obtained from the process activity and included not only the final part or product, but also many other secondary products that were considered waste. Wastes could be from many different sources and, for each one of them, metrics—which vary for each manufacturing technology—should have been correctly defined.

By defining this framework and customizing it for a specific manufacturing technology, we were able to verify the proposal with a set of experiments bounded for an actual research issue.

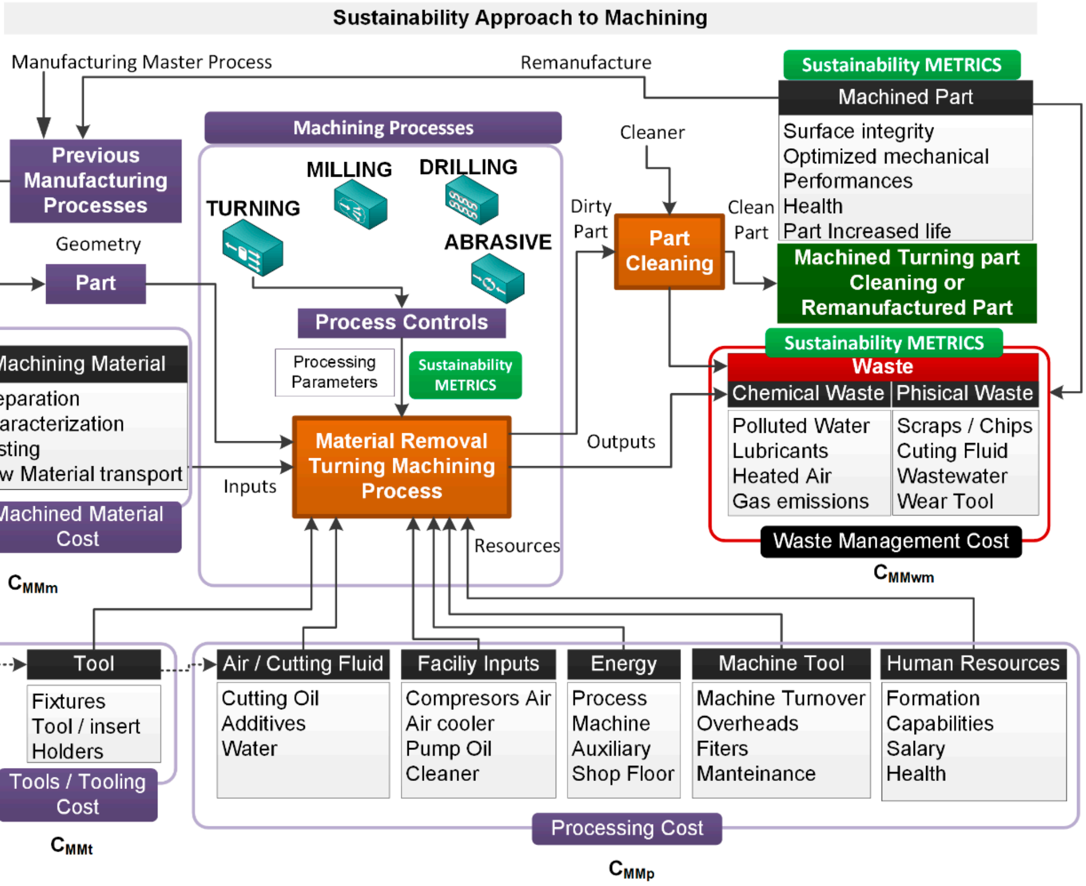


Figure 1. An approach to sustainability research in turning machining applications.

In our proposal for the validation of the approach in turning technologies, we limited the use of sustainable metrics. Evaluation of the manufactured part results was connected with the efficiency of the operation and, therefore, with the optimization of the economical, technological and sustainable objectives. The selected metric—among a list of possible ones—was surface integrity, because it could be related with machining parameters, as initially presented in Figure 1. This is a key issue in industrial processes and allows for rapid visualization of the implications of the outputs. In this case, the better the surface integrity, the lower the sustainability impact.

2.3. Experimental Procedure

The experiments were arranged for basic turning operations due to a special interest in machine manufacturing and for the purpose of improving this part of the manufacturing process.

As mentioned, we considered surface integrity among the possible output metrics. From a quality assurance perspective, it is emphasized that the machined part required an analysis of its surface integrity to determine the quality of the machined part for its correct function.

From the point of view of sustainability, an established quality criterion controlled the superficial integrity of the machined part. The purpose of this was to, firstly, accept or reject the part and, secondly, consider it as a wasted part or suitable to be remanufactured.

For this case study, we defined a procedure for measuring the surface integrity metric and managed the various superficial parameters of the final surface separately. To focus the research, we quantified the final surface roughness and superficial microhardness, and also performed a metallographic analysis to evaluate the results in accordance with the design requirements.

The procedure considered the inputs, process activity, outputs and controls as stated by the framework and was customized to our research aims, as seen in Table 1.

The raw material was the main input, which was characterized both chemically and mechanically. In order to support the experimental method for the material removal turning process, a set of machining features had to be defined with their corresponding turning parameters. The machined or remanufactured part was the output and we fixed, as a sustainability metric, the surface integrity analysis, as it was required to give feedback to the control parameters.

As stated previously, the raw material characterized and selected for this study was the AISI 1018 steel as it has a wide range of industrial applications. The test stock part has a cylindrical geometry 25.4 mm in diameter and 70 mm in length. The chemical composition and mechanical properties were obtained with suitable techniques to ensure validation of both the methodology and subsequent results. Through chemical composition tests, the raw material was categorized as a heat-treated steel. The spark spectrometer equipment used for metal analysis was a Q2 ION optical emission spectrometer (OES), from Bruker firm, with the OES software Elemental Suite. Based on chemical parameters, the results confirmed that the raw stock belonged to the AISI 1018 steel group.

Table 1. Experimental methodology for surface integrity.

Inputs	Process	Outputs	Controls
Raw Material Characterization • Chemical Composition • Mechanical Properties **Machining Features** • Machining Condition • Workpiece Material • Cutting Tool Material **Turning Parameters** • Feed Rate • Depth of Cut • Cutting Speed	Material Removal Turning Machine Process	Machined Turning Part Cleaning or Remanufactured Part	**Surface Integrity** • Roughness • Microhardness Test • Surface Metallographic Analysis • Mechanical Performance • Electron Microscopy

Table 2 shows the results obtained from the chemical composition study. Although manganese was not within the established limits, it was considered that the absolute variation value was very small and, therefore, that the error was a minimum. This variation was due to the fact that the raw material was supplied from a special batch that was specially requested and that we wanted to evaluate.

Table 2. Raw material chemical composition for AISI 1018.

Results	% C	% Mn	% P	% S
Measured Values	0.15	0.57	0.031	0.017
AISI 1018 (ASTM A108)	0.15 < C < 0.20	0.6 < Mn < 0.9	≤0.04	≤0.05

For the experimental procedure (Figure 2), the main features of the technological process that were considered were the machining condition, work piece material and cutting tool material.

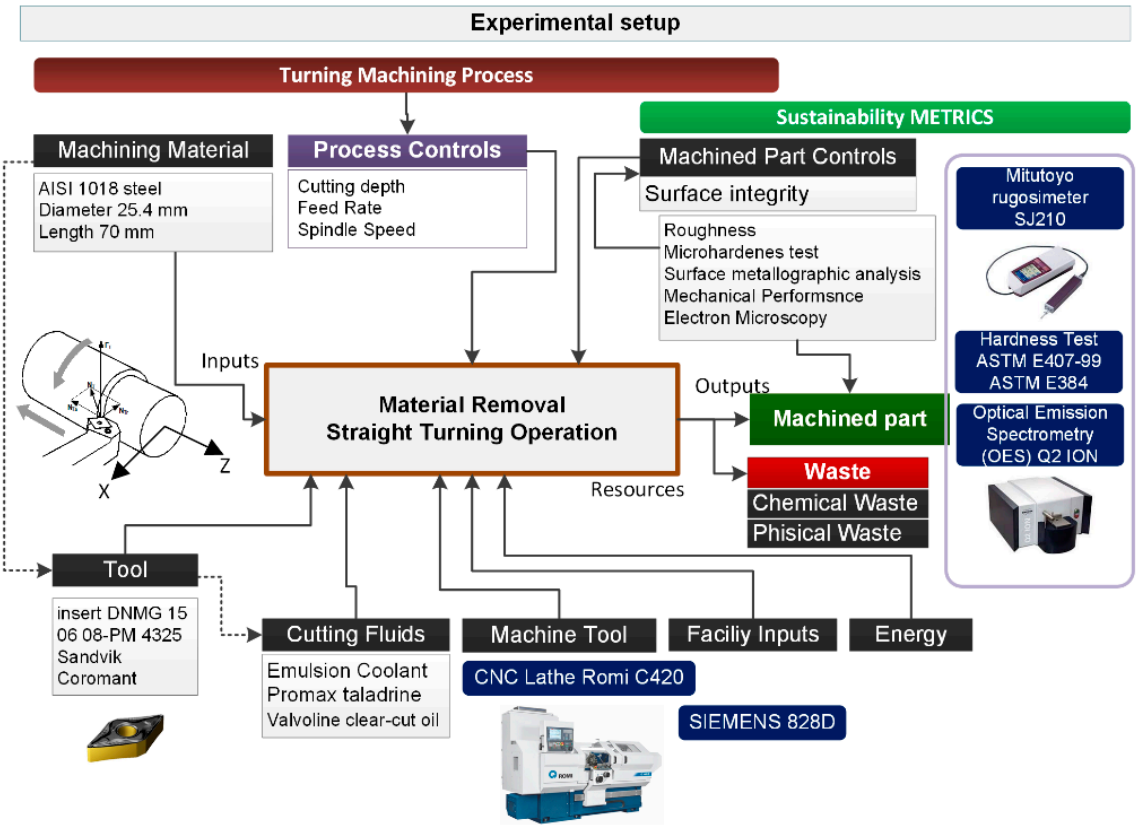


Figure 2. Experimental setup.

The machining conditions outlined for the experiment were a turning machining operation with emulsion coolant. Promax Taladrin was used as the metalworking fluid (Valvoline clear-cut oil), while the cutting tool selected for this operation machining was the turning insert DNMG 15 06 08-PM 4325 from Sandvik Coromant. The cutting parameters defined for this study were the cutting depth, feed rate and cutting speed, with a set rotation speed. The experimental method considered a fixed spindle speed of 1200 rpm, with depth of cut and feed rate as variables.

In order to define a distinct set of experiments, the turning operation variables were modified to design two case studies (A and B), as outlined in Table 3. For Case A, which had a constant or fixed feed rate parameter (f_n) of 0.2 mm/rev, the cutting depth $\left(a_p\right)$ was varied. The rotation speed (n) was fixed for all three tests as well. For Case B, the feed rate (f_n) was varied, while the cutting depth $\left(a_p\right)$ and rotation speed (n) were both fixed.

Note that we limited the experiments to three levels of variation in both cases because the research project objectives directed the experimental work towards recommended cutting conditions. These conditions are those in which a worker or process planner would face in the industry.

Table 3. Design of experiments.

	Case A Constant Feed Rate			Case B Constant Cutting Depth		
Cutting Depth (a_p) (mm)	0.5	1	1.5	1	1	1
Feed Rate (f_n) (mm/rev)	0.2	0.2	0.2	0.3	0.4	0.5
Spindle Speed (n) (rpm)	1200	1200	1200	1200	1200	1200

The experiments of turning operations were carried out on a CNC Lathe Center Romi C420 with a SIEMENS 828D numerical control. The operation process and strategies were defined and validated with the SolidCAM application. Computer-aided manufacturing process planning was applied to control the machining characteristics and selected turning parameters for the test examples, with an initial stock part 25.4 mm in diameter and 70 mm in length. The six experiments were performed following the conditions shown in Table 3. The average surface roughness was selected as a parameter to control the surface integrity and was measured with a rugosimeter (Mitutoyo SJ210).

For the surface metallographic analysis, hardness was first analyzed following the ASTM E407-99 and ASTM E384 standards with a Vickers HV_{200gf} microhardness measurement device, applying the corresponding load during 15 s. The last stage proposed by the methodology established the link between the manufacturing process, deformation of the material and variation of the mechanical properties, as suggested by Pawade [24] and Argawal [25].

According to Cahoon, the mechanical performance of microhardness is an adequate parameter to calculate the yield strength (σ_y) of a material. The relationship between these parameters is shown in the following equation [26].

$$\sigma_y = \left(\frac{H}{3}\right) * (0.1)^{(m-2)} \tag{1}$$

Equation (1) represents a relationship among mechanical characteristics, where H is the hardness obtained from the test on the Vickers scale and m is the coefficient of hardening by deformation established by Meyer, which is equal to 0.26 for low carbon steels [27].

Furthermore, strains (ε) involved in plastic deformation due to machining operations can be related with yield strength as stated in the following equation, where C is a constant value of 0.801 [24].

$$Ln\ \sigma_y = Ln\ C + (m-2) * Ln\ (\varepsilon) \tag{2}$$

$$\varepsilon = e^{\frac{(Ln\sigma_y - LnC)}{(m-2)}} \tag{3}$$

Therefore, Equation (2) represents a mathematical model of the relationship between mechanical properties, such as yield strength, and deformation and mechanical characteristics, such as the strain-hardening coefficient, with the deformation produced in the region affected by machining.

3. Experimental Results and Discussion

Once the set of experiments was completed and the data collected, the results were analyzed to characterize any surface integrity changes due to machining operations and reveal the effects of parameters on the AISI 1018 turning process. A roughness analysis, metallographic surface analysis and mechanical performance analysis were performed as the first step of the overall project.

3.1. Roughness Analysis

The influence of the machining parameters on surface roughness may be seen in Figures 3 and 4. As shown in Figure 3, when the cutting depth was increased from 0.5 mm to 1 mm, the surface roughness of the final part's machined surface tended to decrease by about 50%, thereby showing an increase in surface quality (Case Study A). However, if the cutting depth was increased further to values greater than 1 mm, the roughness slightly increased, again affecting the final surface quality of the final part.

For Case Study B (Figure 4), when the feed rate was increased during the cutting operation, the surface roughness had a distinct tendency to increase its value, resulting in a worse surface quality. In other words, the positive slope shown in Figure 4 indicates that, for machining external elements in precision manufacturing, the surface quality becomes increasingly coarse in response to greater feed rates. This could lead to premature failures. Similar studies completed by Lin [28] and Bordin, Bruschi and Ghiotti [29] have indicated that the surface quality is smooth and bright when obtained at feed rates lower than 0.1 mm/rev.

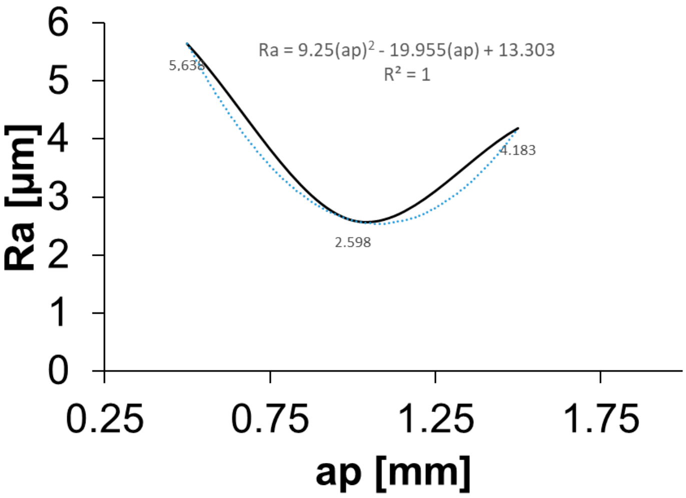


Figure 3. Influence of machining parameters on the roughness of AISI 1018. The effects of feed rate were kept constant.

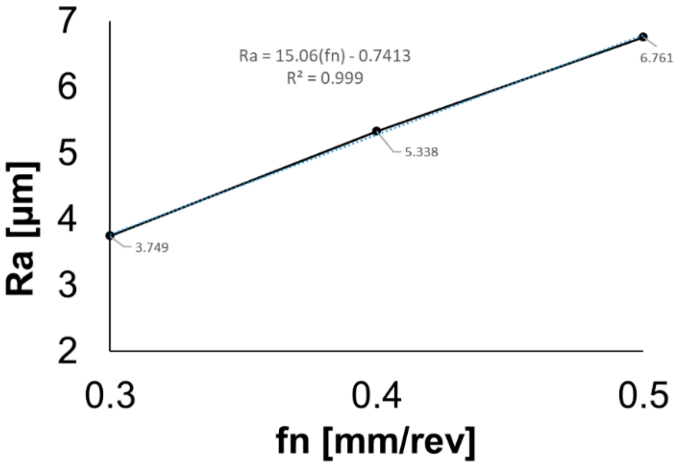


Figure 4. Influence of machining parameters on the roughness of AISI 1018. The effects of depth of cut were kept constant.

3.2. Microhardness Analysis

The material hardness after the machining process was also evaluated. This was measured from the surface towards the center of the AISI 1018 shaft, obtaining an average value of hardness of 206 ± 10 HV_{200gf}. As shown in Figures 5 and 6, the machining process had a significant effect on the microhardness in terms of both the cutting depth and feed rate. The highest values of microhardness were obtained with indentations made at depths less than 100 microns, with an average value of 236 HV_{200gf}, corresponding to the area of greatest plastic deformation. From this depth, the hardness decreased to a horizontal asymptote, obtaining the value of the original stock material. These results demonstrate that both cutting depth and feed rate have an important role in surface hardening results after machining AISI 1018 steel.

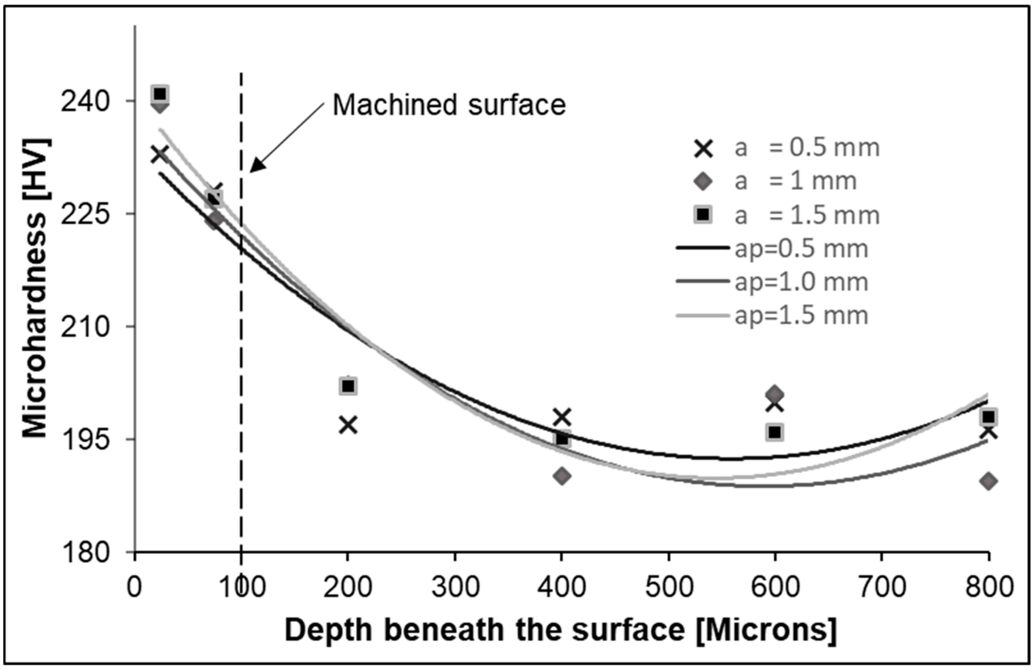


Figure 5. Influence of machining parameters on the microhardness of AISI 1018.

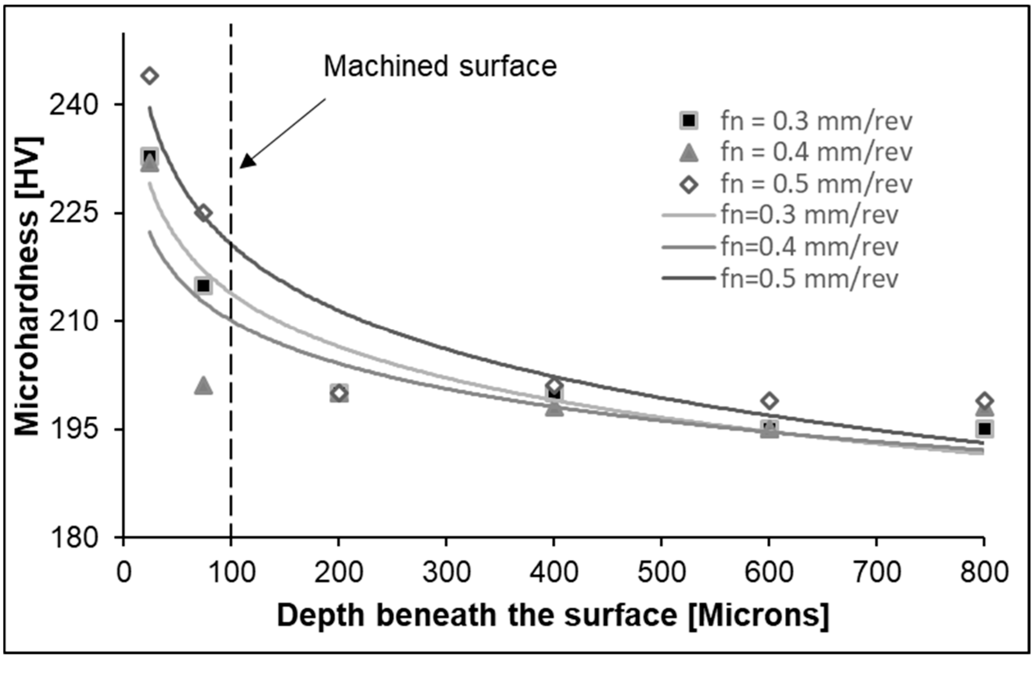


Figure 6. Influence of machining parameters on the microhardness of AISI 1018.

3.3. Surface Metallographic Analysis

After the roughness and microhardness analyses, the grain size of the base material was measured before and after machining in order to determine the influence of machining on microstructure variations. The grain size in the machined area and in the center of the shaft was measured following the Standard Test Methods for Tension Testing of Metallic Materials, ASTM No 8.

The microstructure evolution results from Case Study A were almost the same as those obtained from Case Study B. As a general pattern, there was great deformation caused by contact between the cutting tool and the surface of the work piece. As shown in Figure 7, the ferrite (light color) and pearlite (dark color) grains elongated in the cutting direction. The resulting plastic deformation produced work-induced hardening, which increased the microhardness of the machined surface in response to the increase in cutting depth and feed rate.

The superficial plastic deformation, and therefore the microhardness, is very sensitive to variation in the cutting depth and feed rate parameters.

In order to have a numerical reference to the results, Table 4 was generated to show the final value of the plastic deformation induced in the material in response to the contact between the cutting tool and the work piece during machining of the surface (Case A). From this table it is possible to determine that, as the depth of cut increases in steps of 0.5 mm, the thickness of the plastic deformation layer is also increased.

Table 4. Plastic deformation with constant feed rate (Case A).

a_p (mm)	Measure 1 (µm)	Measure 2 (µm)	Measure 3 (µm)
0.5	28.37	27.73	28.08
1.0	39.75	34.20	37.33
1.5	42.60	42.71	43.99

Figure 7 indicates the plastic deformation depth reached in the case study. For each one of the measures 1, 2 and 3 the image shows where the data was obtained.

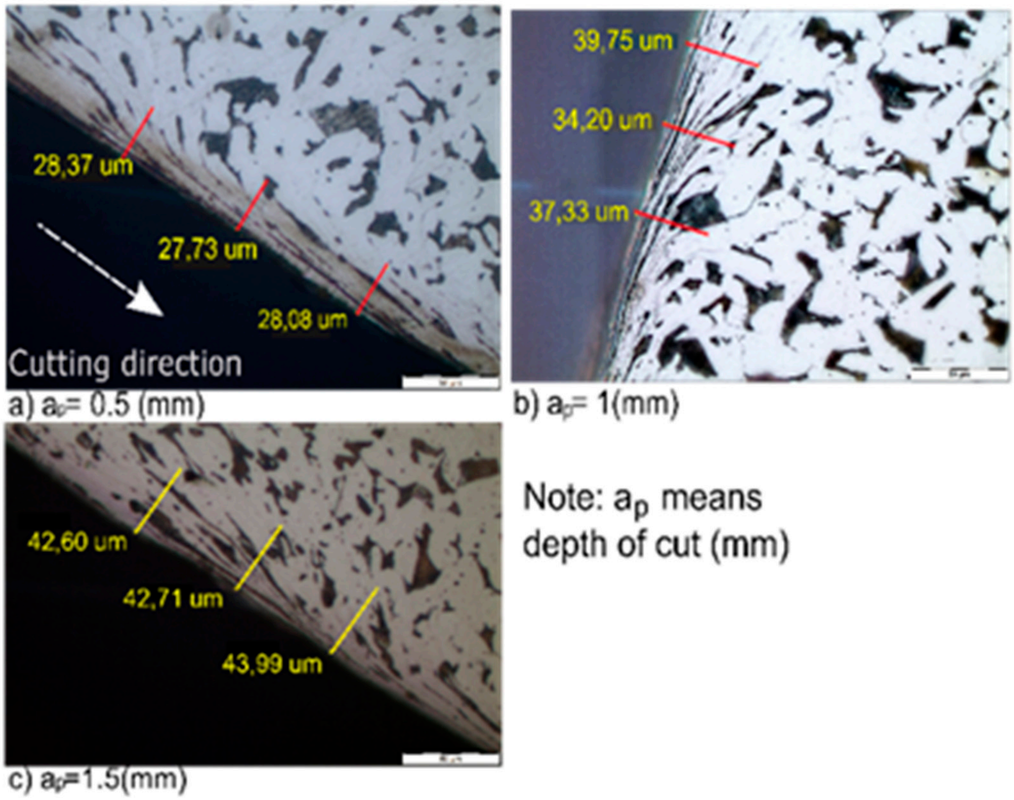


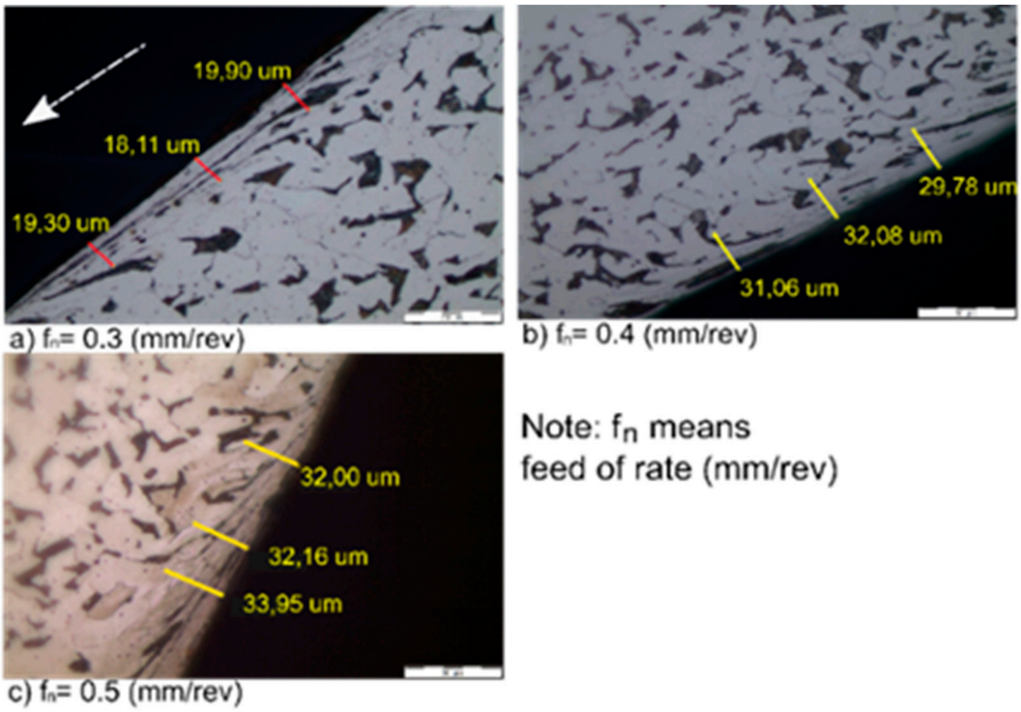
Figure 7. Plastic deformation with feed rate constant (Case A), 500×.

For the same reasons, Table 5 was generated to show the plastic deformation induced in the material in response to variation in the feed rate. The high levels of plastic deformation observed are an effect of the increase in this parameter. However, these values are lower compared to those obtained by varying the depth of cut, so these results do not correspond to microhardness values.

Table 5. Plastic deformation with depth of cut kept constant (Case B).

f_n (mm/rev)	Measure 1 (μm)	Measure 2 (μm)	Measure 3 (μm)
0.3	19.90	18.11	19.30
0.4	29.78	32.08	31.06
0.5	32.00	32.16	33.95

Figure 8 indicates the plastic deformation depth reached in the second case study. For each one of the measures 1, 2 and 3 the image shows where the data was obtained.



a) f_n= 0.3 (mm/rev)
b) f_n= 0.4 (mm/rev)
c) f_n= 0.5 (mm/rev)

Note: f_n means feed of rate (mm/rev)

Figure 8. Plastic deformation with depth of cut constant (Case B), 500×.

3.4. Mechanical Performance Analysis

For the mechanical performance analysis, the yield strength and strain mechanical properties of the final machined surface were obtained by applying experimental data from the microhardness tests to Equations (1) and (3).

Figures 9 and 10 correlate the yield strength with the measured material hardness. These figures demonstrate that changes in feed rate or cutting depth produce a positive slope variation in the material's yield strength.

The linear regressions obtained from plotting microhardness against predicted yield strength indicated a proportional tendency, wherein the yield strength increased as the microhardness increased.

Figure 11 presents the strain distribution generated by the tool at the moment of cutting operation, which was found to be greater in the subsurface layer of the machined area. At a greater depth in the deformed area this effect disappears, and a very homogeneous behavior pattern is observed.

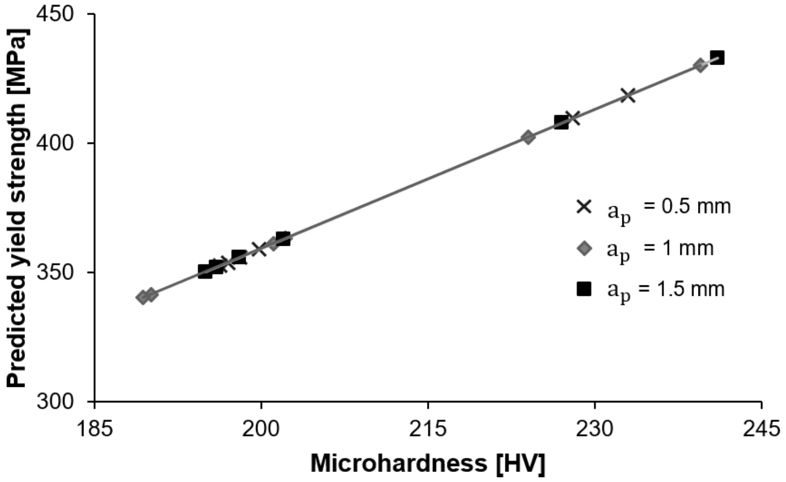


Figure 9. Yield strength versus microhardness with a change in cutting depth.

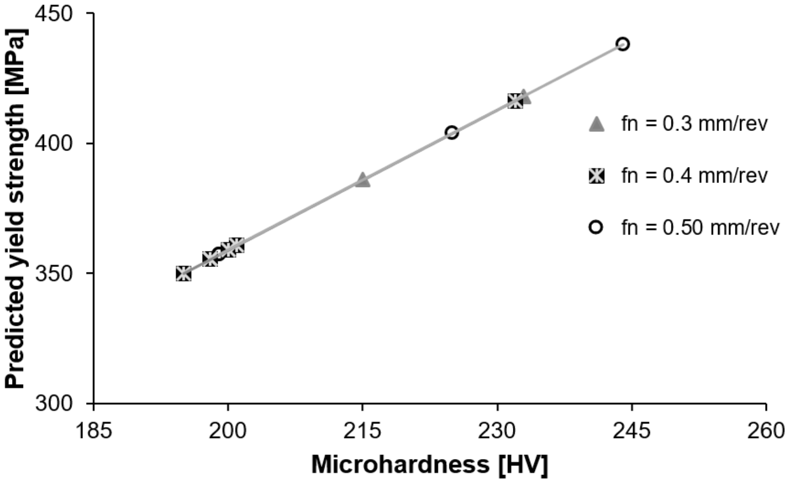


Figure 10. Yield strength versus microhardness with a change in feed rate.

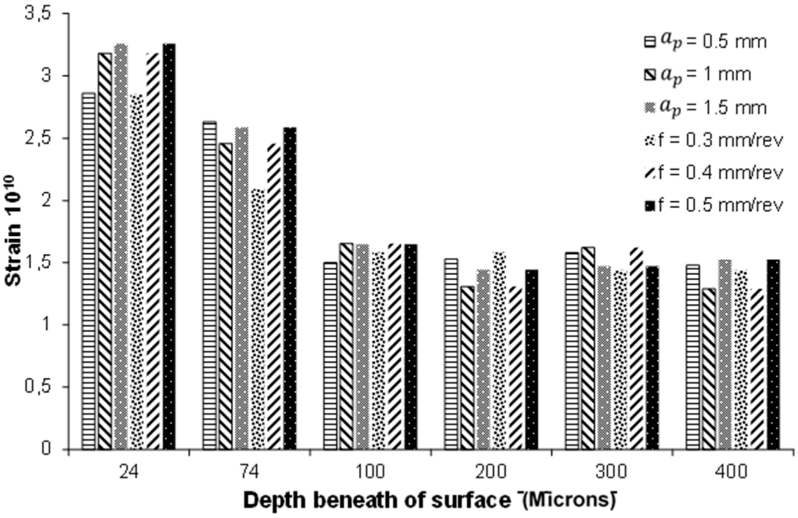
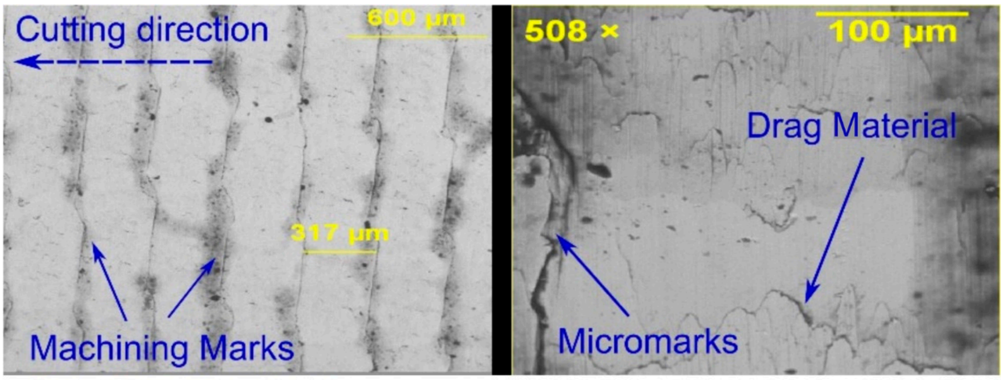


Figure 11. Behavior of strain versus depth beneath the surface.

3.5. Electron Microscopy Analysis

In order to validate the procedure, the quality of the surface and surface texture were characterized by SEM analysis. Figure 12 shows marks and micro-cracks on the machined surface, generated by displacement of the cutting tool when separating the chip.



75x **508x**

Figure 12. SEM of the longitudinal advance of the cutting tool.

4. Discussion

As this experimental work confirms, there is a clear influence on surface integrity by machining parameters. Each parameter has a particular impact on the surface roughness in the machining manufacturing operation. Among the parameters tested in the experiments, we found that the feed rate had the clearest influence, with a positive slope regression line in the range of 0.3 mm/rev to 0.5 mm/rev.

With reference to the results pertaining to a cutting depth between 0.5 mm and 1 mm, it is clear that an increase in the cutting depth generates a favorable result, as the surface roughness is reduced by more than half. This is contrary to the effect observed for a slight increase in the feed rate. However, it was noted that increasing the cutting depth above 1 mm created a change in the slope, with the surface roughness instead increasing in value as the cutting depth increased.

The increase in the material hardness (206–236 HV_{200gf}; 14.5%) of the two machined part surface samples is due to two main causes. Firstly, the machining operation causes micro superficial plastic deformation, which modifies the initial property. Secondly, direct effects on the ferrite and perlite phases—which are also deformed—cause displacement and an accumulation of dislocations in this region that increase the yield strength, the mechanical resistance and, therefore, the hardness.

Plastic deformation in the machined part surface was highly influenced by depth of cut, with the results showing an increase in the strain with an increase in the depth of cut. In addition, an increase of the crystal geometry from 28 to 44 microns was observed. When the feed rate was set to variable and the depth of cut kept constant in the experimental method, a 29.4% reduction in the strain was observed.

In terms of sustainability, our results can help engineers to select manufacturing parameters when elaborating the process plan in the context of this study. In this work, the number of indicators is limited, but the key issue is to have more of them and to link them with their general sustainable metrics—which are not included, as shown in Figure 1. This approach enriches previous works, as it relates pragmatic metrics with more general ones aligned with the company´s sustainable strategy. A small decision in the value of parameters could generate great quantities in terms of energy saving.

5. Conclusions and Future Work

The main objective of this work was to carry out a sustainability analysis of AISI 1018 steel turning operations under the criterion of superficial integrity. Surface integrity is a key point in quality control, hence results obtained from current study cases encourage the prediction of surface integrity performance according to established machining parameters. This work was made under the umbrella of a sustainable approach to manufacturing systems.

The validation study revealed that the correct combination of a limited number of cutting parameters can allow for control of the surface integrity in machining operations. In the case of turning AISI 1018, with adjustments in cutting speed, feed rate and cutting depth parameters, we have indicated that it is possible to obtain confident degrees of surface quality in part features due to micro plastic deformation, which has an effect on the life cycle of the part.

Analysis of superficial integrity in a machined part helps to discover possible manufacturing faults that could be due to errors in the manufacturing process plan or its corresponding parameter definitions. The criterion of superficial integrity allows users to have more effective control of the manufactured parts. It helps to avoid failures that cannot be directly observed by the worker, thereby improving the performance of the manufactured part in fulfilling sustainability criteria and providing feedback for decision making.

Although this work has presented preliminary results for a potentially wide study of sustainability in the process of machining AISI 1018, some future works should be carried out to increase knowledge on this issue. This study could be enriched by including new technology-specific metrics; for example, cutting power outputs or facilities consumption. However, this will complicate data acquisition with multiple objectives, and is an issue for advanced research.

Our approach could also be applied to other machining operations, such as milling or drilling, in order to predict possible causes of failure in the machined surface according to the operating conditions of the process and as part of the decision making procedure.

Complementary works on green manufacturing will find optimal conditions when analyzing the impact of other variables in the process, such as the conditions of wet machining, dry machining or minimum quantity lubrication (MQL).

Fulfillment of the manufacturer's requirements should also include achievement of design dimension tolerances, surface finishing, material surface hardness and treatments that allow for better quality manufactured parts.

Industrial machining processes, such as turning and milling, must adequately define the cutting tools and optimized process parameters that should be applied in order to ensure the sustainability of the process and manufactured products.

Finding the operation conditions that minimize failures in the machined part surface, as well as analyzing the superficial integrity, will help to predict future failures, thereby increasing the useful life of the manufactured parts. Consequently, this will also help to achieve a green manufacturing process that meets the sustainable development goals for responsible production and consumption.

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