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SURFACE INTEGRITY IN THE MICROMACHINING: A REVIEW

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Abstract. Increasingly, the manufacturing industry is concerned to produce the components with the great quality. This quality is correlated with desired surface integrity, accuracy of dimensions, burrs, and other defects in machining. Among these aspects, the surface integrity of the machined components can be complex to manage because it shows a stochastic behaviour or requires special equipment for measuring. Thus, the studies on surface integrity are necessary to understand the surface integrity phenomena and ensure the desired quality. However, if lower values for surface integrity are desired, the micromachining can be a solution because it exhibits closest matches the desired range. This paper shows a review about the surface integrity in conventional machining, but its main purpose is to discuss the results of the literature and the advantage of the surface integrity when the micromachining process is used.

1. INTRODUCTION

The quality of mechanical components should be controlled in all manufacture process, because some parameters in process such as surface roughness, geometric errors, white layer, and others are essential to guarantee a great performance these components. In the finishing process, this control of the process should be more dedicated and attentive to provide excellent surface quality. The surface finish is one of indicators for the quality control of machining operations directly linked to cutting process conditions (cutting parameters, tool, workpiece material, cooling system, occurring phenomena, machine-tool, and others) [1]. An example is the surface roughness of the dies and moulds that affect directly the quality of the injected parts. Moulds are used for injection moulding lenses or dies used for precision forging of automotive drive train components that need high quality [2].

The goal of quality in engineering is to make products that are robust concerning to all noise factors and the most important stage in the design of an experiment lies in the selection of control factors [3]. The developments of new tools with materials more tough, new coating and/or geometries, such as the wiper tools, or processes more modern, as the use of High Speed Machining, are pointing to the development of research that should be explored in the next years.

Bouzakis *et al.* [4] studied the milling with ball nose end mills aiming to understand the chip formation mechanisms, the cutting force, the tool de-

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flections, and achieve low surface roughness values. Tang *et al.* [5] studied the limits of stability during the high-speed finishing in the milling of the steel with 0.45% of Carbon, hardness of 24 HR_C, and the spindle speed between 5,000 to 17,000 rpm. Souto-Lebel *et al.* [6] investigated the distribution and defect size induced by ball nose-end finishing after the milling of the AISI 4150 with cutting speed of 300 m/min.

According to Suresh *et al.* [7], the hard turning is used in semi-finishing and finishing in the automobile industry (transmission shafts, axles, and engine components), and the aircraft industry (flap gears, landing struts, and aerospace engine components). It can be justified as hard turning when the finishing of gear components is around 60% of reduction in machining time than grinding process. It is the reason that has as trend to replace the grinding process with the turning process to directly rough and finish in the machining of hardened bearing components prior to super-finishing.

This paper discusses about the surface integrity in the machined surface obtained in the micromachining processes. It also is composted by a brief literature review about the surface integrity in the conventional machining. The aim of this paper is to propose the usage of the micromachining as finishing operation to obtain the smallest values of surface integrity parameters.

2. SURFACE INTEGRITY

Surface Integrity (SI) is important to safety of strategic industries (as aerospace) or industries of capital goods that use machining processes (as forging dies, plastic moulds, and press tools). The influence of each machining parameter needs to be known, together with interactions, in order to allow at least, a “pseudo-optimization” of SI. The machining parameters, tools, and operation selection are very important on the machining [8].

The incessant need for improved the surface integrity and enhanced functional performance of manufactured components has long worked as a driving force in the growth of new production methods and high performance manufacturing technologies. Today, new technologies in machining processes and high-precision engineering have enabled the miniaturization in manufacturing of several industrial components. This in turn has required the use of advanced methods to provide an accurate characterization during the assessment of the nature of these alterations produced in very thin layers of the machined surface [9].

Ginting and Nouari [10] researched the surface integrity on the milling of titanium alloy Ti-6242S using uncoated and Chemical Vapour Deposition (CVD) coated carbide tools. They found that the surface roughness, in the Ra scale, produced by the uncoated carbide and the CVD-coated carbide tools ranged from 0.39 to 0.72 μm and from 0.43 to 0.69 μm, respectively. Bissey-Breton *et al.* [11] investigated the surface integrity on the super-finishing turning of pure copper using carbide insert tools. They analysed the layer thickness affected by turning process, surface roughness, texture indexes and the strain induced on the surface.

2.1. Surface roughness

Among the many methods to quantify and qualify the surface integrity, the surface roughness is a method widely used and considered as the primary indicator of the quality of the surface finish [12]. The surface roughness can be influenced for all parameters and phenomena that occur during the cutting. A set of parameters of influence surface roughness is diagrammatically displayed in the Fig. 1 [13].

According to Mhamdi *et al.* [14], there are many parameters used in the literature associated with surface roughness. The average surface roughness (R_a) is an arithmetic value of the profile from centre line being the most popular parameter of 2D surface roughness. In 3D surface, the most widely used are the arithmetical mean of the surface (S_a) and the surface roughness parameters (S_q). Lahiff *et al.* [15] cited that if the surface finish (R_a) was the parameter used to define tool life, the maximum nose radius was 0.8 mm, because a smaller nose radius has a negative effect on the surface finish of workpiece.

In the finish of hard turning of AISI 5140 steel (60 HR_C), the surface roughness obtained were 0.28 μm (R_a) and 1.55 μm (R_z) using wiper inserts and feed of 0.1 mm/rev providing similar surface roughness obtained (R_a = 0.25 μm and R_z = 1.62 μm) using traditional feed rate and feed rate of 0.04 mm/rev [16]. Özel *et al.* [17] using wiper tools to higher feed rates in the turning of AISI D2 steel (60 HR_C) was attained the surface roughness (*Ra*) (range of 0.18 to 0.20 μm), which the better surface finishes was obtained at the lowest feed rate and highest cutting speed combination.

In hard turning of AISI D2 steel using ceramic tools and appropriate machining parameters, the surface roughness values achieved can correspond a high dimensional precision (R_a < 0.8 μm). Furthermore, the cutting time influenced the surface

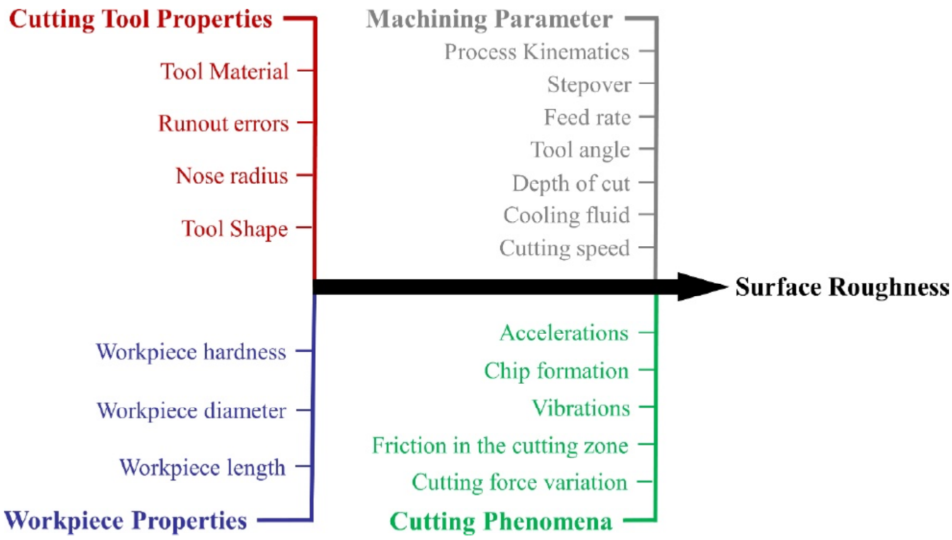

Fig. 1. Fishbone diagram with the parameters that affect surface roughness (Adapted from [13], with permission from Elsevier, License Number: 3499070292705).

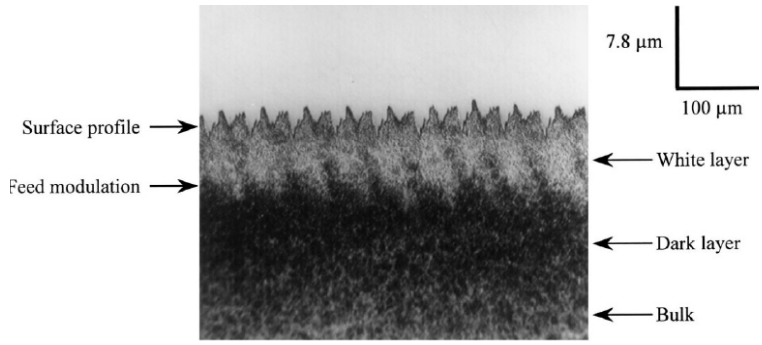

Fig. 2. White layer formed at a hard turned surface of 52100 steel (Adapted from [24], with permission from Elsevier, License Number: 3499071045162).

roughness in 32%, and the feed rate influenced the specific cutting pressure and surface roughness, 64.1% and 29.6% respectively [18].

Devillez *et al.* [19] in the turning of Inconel 718 (44 HR_C) (dry and wet) demonstrated that the surface roughness (R_a) had a tendency to decrease with the increase in cutting speed in dry conditions and the wet condition. However, the values decreased with higher cutting speed values only for values above 60 m/min. Yazid *et al.* [20] observed that experiments of finish turning in the Inconel 718 using carbide tool with TiAIN coating (PVD method) showed that the MQL produces better surface roughness than dry condition.

Brandão *et al.* [21] studied the influence of cooling systems (dry, MQL, cold air) in the surface roughness (R_a) on the turning of Ti-6Al-4V alloy and they observed that the cooling system was less influent than the feed rate on surface roughness. Even so, the cooling systems did not show the same influence and they cited the usage of the traditional MQL system is a good choice to provide best surface roughness values.

Pu *et al.* [22] studied the dry machining and cryogenic machining of AZ31B magnesium alloys. The authors observed that the application of liquid nitrogen cooling decreased about 20% of the irregularities on surface roughness, the better surface finish in cryogenic machining could be assigned to the reduction of temperature through effective cooling by applying liquid nitrogen.

Beyond surface roughness and form, the surface finish consists of waviness on surface that is a kind of imprecision in surface length greater than the surface roughness wavelength and less than the waveform error. The surface roughness wavelength in the feed direction is equivalent to the feed rate in units of distance [23].

2.2. White layer

The microstructural changes, often higher than the bulk, are called "white" because it resists to standard etchants and appears a white under analyses in an optical microscope, as can be seen in Fig. 2. It has been suggested to have an untempered martensitic structure. Large plastic deformation and/or rapid heating-cooling are possible in the formation of these mechanisms. White layers seem to be detrimental to product performance and therefore require a post-finishing process [24].

According to Ulutan and Ozel [12] the quenching mechanism of rapid heating and cooling create the white and dark layers below the bulk, and it transforms the surface from austenitic to martensitic structure. However, the white layer formation also occurs in the absence of high temperatures that are enough to allow phase transformations to occur due to mechanical effects.

In the literature, tool wear was suggested as the most influential parameter on white layer formation, but this explanation was not implication that optimization of surface structures or minimization of white layers is possible [24]. However, Bosheh & Mativenga [25] investigated the finish turning of H13 (54 to 56 HR_C) and did not observed an positive correlation between tool wear and white layer thickness. Therefore, abrasive wear in HSM cannot be assumed as responsible for white layer formation. According to Hosseini *et al.* [26], the hard turning of AISI 52100 (747±10 and 715±12 HV30) revealed that the thickest white layer was obtained with the highest cutting speed combined with the highest flank wear.

2.3. Residual stresses

Residual stresses are the stresses remaining into a body where there are no external forces applied on the body, inhomogeneous inelastic deformation, and the stress created by solidification mechanism (microscopic level). Residual stresses are generated at the grain boundary or other nearby imperfections in the material. In the machining process, the residual stresses are induced by the inhomogeneous inelastic deformation created by the very action of cutting and when the cutting tool is retracted, and the workpiece is released. Thus, the stresses that remain in the workpiece, after it is cooled to room temperature [27].In their study about residual stresses, Maranhão and Davim [28] affirmed that important aspects on machining of materials are:

- Compressive residual stresses generally improve the performance and life component;
- The influence of the process parameters on residual stresses is as follows; feed rate, tool nose radius, rake angle;
- Residual stresses are mostly influenced by feed rate and nose radius;
- Increased feed generates significantly higher compressive stresses;
- The residual stresses mechanism is influenced by process parameters in general.

Tang *et al.* [29] investigated the influence of residual stresses on the milling of aluminium alloy 7050-T7451. They observed that the wear on tool's flank and depth of cut have effect on superficial residual stresses. The use of small depth of cut generated minimum tensile and compression stresses on a very small surface, in addition to mechanical and thermal load (significantly) affecting the thickness and residual stresses layer.

Madyira *et al.* [30] studied the residual stresses on the turning of Ti-6Al-4V titanium alloy and observed that maximum principal stress was typically aligned along the main cutting direction and the induced residual stresses by the cutting process were mostly in compression.

Pu *et al.* [22] measured the residual stresses in circumferential and axial directions and concluded that the residual stresses were close to zero. The authors used a tool with edge radius of 30 μm and liquid nitrogen as cooling system. They created a smaller compressive area than dry machining with tools of edge radius of 70 μm and the trend was opposite. According to the authors, this occurred because the cryogenic machining led to an increase of 72% and 97% in compressive areas, respectively, in circumferential and axial directions compared with dry machining.

Caruso *et al.* [31] investigated the hard machining of AISI 52100 steel and observed the increase of cutting speed and the maximum compressive residual stresses. The authors support that mainly on the axial direction, stress below surface increases, and it is shifted further away from than surface.

Devillez *et al.* [19] observed that residual stresses in dry and wet conditions appeared when the tensile stress was limited and when a lubricant was used. However, when the lubrication was reduced and the cutting speed also increases, an equivalent tensile stress asset value occurs for a cutting speed of 80 m/min.

2.4. The usage of the FEM

To improve the comprehension about the surface integrity, some researchers have used the Finite Elements Method (FEM) to study the residual stresses, surface roughness, white layers and other behaviour of the machining processes. Ee *et al.* [27] used a 2D model to study the residual stresses

Table 1. Roughness in micromachining processes.

Researchers	Material	Process	Roughness (μm)
Palani *et al.* [43]	Tungsten electrode	Turning	R_a = 0.029 to 0.58
Liu and Melkote [44]	Al 5083-H116 aluminium ally	Turning	R_t = 2.82 to 4.63
Li and Chou [49]	SKD 61 steels (38 HR_C)	Milling	R_a = 0.1 to 1.2
Wang *et al.* [40]	Brass	Milling	R_a = 0.013 to 0.073
Min *et al.* [50]	Austenitic stainless steel 304	Milling	R_a = 0.190 to 0.300
Lauro *et al.* [45]	AISI H13 steel (44 and 46 HR_C)	Milling	R_a = 0.088 to 0.223

induced by orthogonal machining. Valiorgue *et al.* [32] used a 3D model to study the residual stresses in finish turning of AISI 304L stainless steel with a coated carbide tool (TiN coating). They proposed a model that does not simulate the chip formation and the material separation around the cutting edge, but only onto the thermo-mechanical loadings applied onto the machined surface.

Ramesh and Melkote [33] used the FEM to study the white layer formation in orthogonal machining of AISI 52100 steel (62 HR_C) using the CBN tool. They used an explicitly incorporated model with effects of stress and strain on the transformation temperature, volume expansion and transformation plasticity that showed predicted values and trends of white layer thickness. These effects are in good agreement with the measured values and trends when compared to experimental validation.

Attanasio *et al.* [34] used numeric (2D and 3D) and experimental tests to study the formation of layers on the orthogonal hard turning of AISI 52100 steel. They found that the thickness of white and dark layers increases with increasing of tool's flank wear and high cutting speed generated thicker white layers and thinner dark layers. A small feed rate increases the white layers thickness. On the other hand, the high feed rate decreases the dark layer thickness.

3. SURFACE INTEGRITY IN MICROMACHINING

The study of the micromechanical machining is strongly interested in understand the mechanical cutting processes, because it is a method for creating miniature devices and components with features that range from tens of micrometers to a few millimetres in size [35]. This process offers good results, it is reason why way many researchers are investigating the performance of micromachining and their derivations in several cutting conditions

According to Masuzawa [36] a miniaturization of mechanics devices began with oldest wristwatches parts, the only studies developed in this age. Micro in micromachining indicates "micrometre" and represents the range of 1μm to 999μm; despite this definition, the micro conception can vary with time, person, material, and process.

Ng *et al.* [37] define that the cutting in micro/nano scale would be a chip removal in smaller scale. Micromachining is a precision/ultra-precision machining technology where the tolerances, depths of cutting, and even part sizes are in micro-scale [38].

The micromilling has more highlight between all micromachining processes, because it has great accuracy, low surface roughness, and a high material removal rate, there is a direct relation to the manufacturing of mould and dies [39]. Wang *et al.* [40] have studied the surface roughness on the micromilling of brass, and they observed that the surface roughness increased rose linearly with the increase of tool diameter and spindle speed, but the spindle speed caused a high-frequency vibration caused a high surface roughness.

According to Filiz *et al.* [41], only the main effect of the spindle speed was statistically significant that indicates the possibility of increasing the material removal rate without compromising on surface roughness. Some results of surface roughness, often lower values, can be seeing in the Table 1.

A concern for process control is to understand the induced elastic deflection caused by the cutting and feed forces, because the feed rate and depth of cut are important parameters in preserving surface integrity of the machined workpiece [42]. To develop mathematical models of surface roughness to micromachining applications, the size effects are quite challenging [43].

According to Liu and Melkote [44], it was observed that the surface roughness in micro-turning decreases with feed, reaches a minimum, and then increases with further reduction in feed. They developed a kinematic roughness model where the percentage error was less than 15%, to micro-turning of Al5083-H116 aluminium alloy. It was considered

a) SAE 1045 (25HR$_C$) b) SAE 1045 (51HR$_C$) c) SAE 1045 (62HR$_C$)

Fig. 3. Occurrence of burrs in different material states (Adapted from [47], with permission from Elsevier, License Number: 3499080181637).

the aspects as the effect of plastic side flow, tool geometry, and process parameters. They observed also that the plastic side flow could cause a discrepancy between the theoretical and the measured surface roughness, and it rises and increases due to the strain gradient-induced strengthening of the material directly ahead of the tool.

Aramcharoen and Mativenga [47] studied the micromilling in the AISI H13 steel (45 HR$_C$) undergone to the hardening by vacuum, and it exhibits a structure homogeneous for work piece material with fine grain structure that is preferable for micromachining. They used a micro mill with a diameter of 900 mm and found surface roughness values between 140 and 260 nm. They also affirmed that the best surface finish was obtained when the non-deformed chip thickness was selected to be the same magnitude as the tool edge radius, which is the point, there is a trade-off between the ploughing effect and conventional shearing mechanisms.

Lauro *et al.* [45] analysed the surface roughness in the micromilling of the AISI H13 steel (44 – 46 HR$_C$) with different grain size (39.9 and 497 μm) using a micro end mills with a diameter of 0.5 mm, two values of cutting speeds, and two values of feed rates. They observed a variation between 2.0% and 51.1% to the R_a and 30.6% and 70.1% to the R_z.

Bodziak et al. [46] studied the surface integrity of moulds, AISI P20 steel (29 HR$_C$) and AISI H13 steel (45 HR$_C$), for micro-components obtained by micromilling and EMD process. They observed that EDM presented white layer exhibiting irregular thickness with a hardness about three times higher than the bulk material, and in separately milled surface some plastic deformations with thickness thinner than 5 μm were detected. The milled surface presented compressive residual stresses and the EDM surface presented tensile stresses, and furthermore the EDM showed highest surface roughness (R_a), about six times, with most aggressive marks and an irregular topography that may increase the polishing time.

The understanding of tool wear is important in the microcutting, mainly during the machining in the hardened materials. Although, the usage of high cutting speeds results in the better surface quality in hardness material, the burrs occur most frequently because of the faster tool wear, see Fig. 3. It can be reduced by identifying of the correct combination between cutting parameter and material [47].

Zhang *et al.* [48] developed an accurate prediction model of surface roughness for micro-turning of AISI 1045 steel based on considering the effect of pile-up formation process, tool geometry and cutting parameters. The authors observed that the best surface roughness can be obtained when the ratio of feed to cutting edge radius reaches 0.1.

4. CONCLUSION

Although the "micro" conception can remind the components of smallest dimensions, the micromachining can be to manufacture components in macro-scale. Through the previous arguments, the use of micromachining can be recommended in the finishing of surfaces that need of high accuracy. This technique offers lower surface integrity values that can provide high efficiency and durability. In addition , the surface can show lower error, as form or dimensions. Thus, if there is a demand of high surface quality machining, the usage of micromachining is a great option to obtain these surfaces. However, this technique requires high control and specials or adapted machines.

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