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A comprehensive study of operational condition for turning process to optimize the surface roughness of object

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ABSTRACT : The demand for high quality and fully automated production focuses attention on the surface condition of the product, especially the roughness of the machined surface, because of its effect on product appearance, function, and reliability. For these reasons it is important to maintain consistent tolerances and surface finish. Also, the quality of the machined surface is useful in diagnosing the stability of the machining process, where a deteriorating surface finish may indicate work piece material non-homogeneity, progressive tool wear, cutting tool chatter, etc. One should develop techniques to predict the surface roughness of a product before turning in order to evaluate the robustness of machining parameters such as feed rate or spindle speed for keeping a desired surface roughness and increasing product quality. It is also important that the prediction technique should be accurate and reliable.

Keywords : Machining optimization; turning; surface roughness; variables; nose radius Chip Morphology; Built-Up Edge (BUE)

I. INTRODUCTION

Surface roughness is an important parameter in manufacturing engineering with significant influence on the performance of mechanical parts. Failures, sometimes catastrophic failures, leading to high costs, have been imputed to a component's surface roughness. Owing to the need for improvement of machining parameters in order to obtain a prescribed surface roughness, new developments have been recently investigated. Indeed the quality of the produced surface roughness cannot be evaluated using only a criterion. Originality/value - A new methodology for determining optimal machining parameters in dry turning based on the measurement of the surface roughness [1].

The next thing is to determine the factors that affect the surface finish :

(*a*) The machining variables or set up variables, which include cutting speed, feed rate, depth of cut. These parameters can be set up in advance. It means that these parameters are controllable. "Controllable" means that these parameters like cutting speed, feed and depth of cut is known – set in advance. But it does not mean that knowing these parameters it is easy to predict the surface roughness. There are many interactions between these parameters and other parameters [2].

(*b*) The tool geometry like nose radius, rake angle, side cutting edge angle, cutting edge. These factors depend on the tool to be chosen for exact machining process. If the tool is qualitative – predictable, then parameters are considered to be controllable. Anyway, it is necessary to keep in mind that such a factor like extensive tool wear can occur. In such a Case tool geometry can not be considered as predictable parameter [3].

(*c*) Work piece and their mechanical properties. If used materials are produced under quality control, the parameter (work piece properties) can be considered as controllable.

(*d*) Auxiliary tooling, and used lubrication. Auxiliary tooling, for example clamping
System can be considered as controllable, if clamping process is done correctly. Clamping problems can be figure out by controlling machined parts waviness or cutting machine, for example lathe, vibration parameters. In some processes like finish hard turning lubrication or cooling liquids are not used. In such a case the factor is omitted.

(*e*) Vibrations between work piece, machine tool and cutting tool. These factors also
Influence the waviness and form errors of the surface proposed.
Turning is one of the main types of machining where material is removed using a cutting tool. It allows rotating parts to be produced using a single-edge cutting tool.

Turning parameters

The most common external turning operations are the following [4]. Many of the same operations exist in internal turning, but these are grouped in the reaming category :

(*a*) Creation of planes -facing
(*b*) Creation of cylinders-straight turning
(*c*) Creation of shapes-copy turning
(*i*) radial groove
(*ii*) threading

The characteristic parameters of a turning operation are (example : straight turning of a cylinder with a diameter d (mm) :

Cutting parameters :

(*i*) The depth of cut a_p (mm)

(*ii*) The feed per rotation f (mm)

(*iii*) The cutting speed v_c (m min^1) which gives the rotational speed N (rev min^{-1})

$$N = 1000 \times Vc/xd$$

The cutting parameters are at the root of the following performance parameters :

(*i*) The feed rate v_f (mm min^{-1}), $v_f = f \times N$

(*ii*) The material removal rate Q ($\text{cm}^3\ \text{min}^{-1}$),

$$Q = ap \times f \times vc$$

Design engineers and product designers are determined to design machines that are efficient, have longer lives, and operate precisely as desired. Today's advanced machine requirements demand design allowances for higher loads and speeds that have led to radical change in the design of bearings, seals, shafts, machine ways, and gears. To satisfy the advanced requirements, machine parts should be dimensionally and geometrically accurate. The quality of a machined surface manifests the accuracy of the process in relation to the dimensions specified by the designer [5].

Machining operations tend to leave characteristic evidence on the machined surface. They usually leave finely spaced micro-irregularities that form a pattern known as surface finish or surface roughness. The quality of the finished product, on the other hand, relies on the process parameters; surface roughness is, therefore, a critical quality measure in many mechanical products [6].

A considerable number of studies have investigated the general effects of speed, feed, depth of cut, and nose radius. Receiving serious attention for many years, surface roughness has formulated an important design feature in many situations, such as parts subject to fatigue load, precision fit, fastener hole, and aesthetic requirements. In addition to tolerances, surface roughness imposes one of the most critical constraints for the selection of machines and cutting parameters in process planning. A larger point angle in combination with softer materials yields a smoother surface. A relatively large depth of cut can produce a smoother surface as well.

Previous studies proved the significant impact of DOC, machining speed, and rake angles on surface roughness. The few studies that have studied nose radius as a factor have failed to eliminate the effect of built-up edge. But very few researchers have studied the interaction effect of nose radius. The material will be defined when a larger nose radius was used and the chip had a thickness value greater than the minimum thickness value.

The combination of both of these factors suggests a significant weight in the relationship. All the previous studies on predicting surface roughness have not included nose radius as a major factor that affects surface roughness.

II. EXPERIMENTATION

Decide tool geometry :

(*i*) Tool material

(*ii*) Choice of operating condition

(*iii*) Stock length

(*iv*) Measured surface finish of a machined parts

(*v*) Using DOE, experiments were conducted, data collected and analyzed

(*vi*) Drew conclusions from the data

(*vii*) Determined the factors/parameters and/or combination of the factors/parameters that significantly affect the part surface finish.

A. Global geometry

The turning tool is comprised of an insert holder and a detachable insert.

The factors that govern the choice of insert holder (overall geometry), for example for a straight turning tool, are :

(*i*) The choice of cutting edge angle

(*ii*) The type of insert (included angle), the shape, the dimensions and the insert attachment method.

(*iii*) The dimensions of the insert holder

These choices are made as a function of :

(*i*) The shape of the part and the type of operation (straight turning, threading…)

(*ii*) The severity of the operation (rough or finishing section, impacts)

(*iii*) The machine's characteristics

(*iv*) Techno-economic criteria (production run size, cost)

At the same time as the insert holder is selected, an insert must be chosen based on selection factors that fall outside the shape and dimensions already selected:

(*i*) Tool material (grade and coating)

(*ii*) Cutting geometry

(*iii*) Corner radius

These choices will be made according to:

(*i*) The type of alloy

(*ii*) Wear resistance

(*iii*) The severity of the operation (rough or finishing section, impacts)

(*iv*) The surface condition for finishing

(*v*) The cost of the insert

Table 1 : Hard cutting materials (ISO 513) .

E.g. of a material's name	HF - N10		HF: Letters that characterise the tool material
			N10: Application group (see table 2)
Group of materials	Material letters	Coated	Description
Carbides	HW	No	Tungsten carbide-based carbide, grain > 1 µm
Carbides	HF	No	Tungsten carbide-based carbide, fine grain < 1 µm
Carbides	HC	Yes	All coated carbides
Diamond	DP	No	Polycrystalline diamond
Diamond	DM	No	Mono-crystalline diamond

Remark : High-speed steel is not used in the turning of aluminums.

B. Tool material

The field of application of grades of cutting material, other than high-speed steel, has been standardized with 2 symbols. Materials that are suited to aluminum alloys are included in Table 1. Among the most common are :

(*i*) HF fine-grain carbide (for good cutting edge sharpness)

(*ii*) HC-coated carbide to improve wear resistance and favor sliding

(*iii*) Highly wear resistant DP polycrystalline diamond for high speeds or abrasive alloys, commonly known as PCD

C. Choice of operating conditions I

Example : straight turning, copy turning

General points

The choice of operating conditions :

(*i*) Cutting speed,

(*ii*) Feed per rotation,

(*iii*) Depth of cut.

is made primarily according to the type of alloy being machined.

The grade and geometry of the tool (angles and dimensions, corner radius). The severity of the operation (section of chips from rough turning, impact machining, finishing) with constraints and limitations relating to quality (precision, surface condition). The machine's characteristics (power, torque, rotational speeds and feed rates). Safety (rotational speed limited by the clamping chuck, by part unbalances) [7].

Techno-economic manufacturing criteria (productivity, cost), which depend on tool life and therefore on the cutting parameters selected.

D. Choice of operating conditions II

Example : straight turning, copy turning

(*a*) *Choosing depth of cut a_p*

In the case of rough turning, this is limited by the turning allowance or by the machine's characteristics (power, "in conjunction with a_p, v_c, f") [8].

In the case of finishing, it is generally low in order to obtain a good level of quality: $0.2 < a_p < 0.5$ mm

(b) Choosing feed f

For rough turning, this is linked to insert geometry (chip control) and pass depth.

Example : $a_p = 4$, possible f of 0.2 to 0.55. This feed must be restricted to prevent chips from jamming in soft and "sticky" alloys.

It is also limited by the machine's characteristics (power, "in conjunction with f, v_c et a_p", and feed rate) For finishing, it is selected according to surface condition, with the help of a geometric formula.

(c) Choosing cutting speed v_c

This choice is made primarily according to :

The type of alloy being machined (especially with respect to any hardening treatment conducted and the Silicon content).

The grade of the tool (grade of carbide or diamond). The severity of the operation (section of chips from rough turning, impact machining, finishing). The machine's characteristics (power, rotational speeds and feed rates)(see example of a power calculation). The limitation of rotational speed by the clamping chuck or by part unbalances. The tool life of the tools selected according to techno-economic criteria.

When turning aluminum alloys, cutting speeds are often lower than in milling, where the rotating tool can be balanced. Hypereutectic alloys aside, cutting speeds can be high without causing significant wear to the tool. That is why the table of conditions on the next page contains basic data that can be adapted to suit the operation-part-machine-clamping-lubricant environment and the wear observed. In addition, unlike steels, reference tool life are not provided [9].

(d) Specific Cutting Force, k_c

Specific cutting force k_c (N mm^{-2})

The specific cutting force is primarily a function of :

(*i*) The material being machined

(*ii*) The feed

(*iii*) Cutting geometry

(*iv*) Tool wears (an increase of 30 to 40%)

The table below gives values of k_c for :

$f = 0.4$ mm

Table 2 : A geometry and a cutting speed that are suited to the material.

Class of material		k_c* new tool	k_c* worn tool
Aluminum alloys:	- forged annealed - cast Si<13	500	700
Aluminum alloys:	- forged aged - cast Si>13	750	1,050
- FGL250 type GL cast-irons		1,250	1,750
- FGS500 type GS cast-irons, R<600 steels		1,500	2,100
R<800 steels, Titanium Alloys		1,750	2,450
R<1000 steels, Austenitic stainless steels		2,000	2,800
R<1200 steels, X200Cr12 annealed tool steels		2,250	3,150
R<1400 steels, Refractory stainless steels		2,500	3,500
Mn X120Mn12 steels,		2,750	3,850
Nickel-based alloys, Cobalt-based alloys		3,000	4,200
60HRC steels		3,250	4,550

Surface condition is determined by several factors :

(*i*) Cutting parameters (cutting speed, feed)

(*ii*) Tool geometry (angle and sharpness of the cutting edge, corner radius, etc...)

(*iii*) The material the cutting tool is made from

The rigidity of the assembly and of the machine, the forming of chips, cutting forces.

Nose Radius. Nose radius is a major factor that affects surface roughness. A larger nose radius produces a smoother surface at lower feed rates and a higher cutting speed. However, a larger nose radius reduces damping at higher cutting speeds, thereby contributing to a rougher surface. The material side flow can be better defined when using a large nose radius. Again, this can be explained by studying the effect of the nose radius on the chip formation. During cutting with a tool that has a large nose radius, a large part of the chip will have a chip thickness less than the minimum chip thickness value. In addition, increasing the nose radius has a direct effect on cutting forces, leading to a significant increase in the ploughing effect in the cutting zone. Increasing the ploughing effect leads to more material side flow on the machined surface. In general, increasing the nose radius increases the level of tool flank wear. Cutting with a large nose radius results in a higher value of cutting forces due to the thrust force component. On the other hand, cutting with a small nose radius prolongs tool life, which can be explained by the reduction in the ploughing force [10].

Edge preparation has an effect on the surface roughness. Although the chamfered tool is Recommended to prevent the chipping of the cutting edge, there is no significant difference in the rate of tool wear. The surface finish generally degrades with cutting time due to tool wear development. Large nose radius tools have, along the whole cutting period, slightly better surface finish than small nose radius tools. Tool wear development with cutting time showed, after high initial wear rate that flank wear land width increases in a linear way. The tool nose radii in the range of 0.8–2.4 mm seem to have no effect on the tool wear process, showing comparable wear rate and similar tool life [11,12].

Feed Rate. Feed rate is another major factor that has a direct impact on surface roughness. Surface roughness is directly proportional to the feed rate. The feed rate produces effective results when combined with a larger nose radius, higher cutting speed, and a smaller cutting edge angle. Regarding the work piece machined with a smaller feed rate, the machined surface shows that extensive material side plastic flow existed. This explains the better surface finish obtained at lower feed rates.

Depth of Cut. The depth of cut has a proven effect on tool life and cutting forces; it has no significant effect on surface roughness except when a small tool is used. Therefore, a larger depth of cut can be used to save machining time when machining small quantities of work pieces. On the other hand, combining a low depth of cut with a higher cutting speed prevents the formation of a built-up edge, thereby aiding the process by yielding a better surface finish

Cutting Speed. Cutting speed has no major impact on surface roughness. It affects the surface roughness when operating at lower feed rates, which leads to the formation of a built-up edge. Higher speeds are important in yielding accurate results. At speeds higher than 300 feet per second, actual surface roughness comes closer to the calculated value of surface roughness.

Built-Up Edge (BUE). A built-up edge (BUE) usually forms at the tip of the tool cutting edge during machining. As the BUE becomes larger, it becomes unstable and eventually breaks up. The BUE is partly carried away by the chip; the rest is deposited on the work surface. The process of BUE formation is continuous, and destruction is continuous. It is one of the factors that adversely affect surface roughness. Although a thin stable BUE that protects the tool's surface is desirable, BUE is generally undesirable. BUE does not form at higher cutting speeds, low depth of cuts, and higher rake angles.

Material Side Flow. One of the factors that deteriorate the machined surface is the material side flow. It is defined as the displacement of a work piece material in a direction opposite to the feed direction, such that burrs form on the feed mark ridges. Work piece material in the cutting zone is subjected to a high enough temperature and pressure to cause a complete plastification of the work piece material. Chip material flow in a direction perpendicular to that of the usual chip flow during the machining of hardened steel has been observed. This material sticks on the new machined surface and causes a deterioration of the machined surface quality, even if the surface roughness is kept within the desired tolerance. In addition, the adhered material is hard and abrasive, such that it wears on any surface that comes into contact with the machined surface. The surface deterioration is mainly attributed to material side flow that existed on the machined surface as a result of machining with a worn tool. In addition, the cutting speed has a significant influence on material side flow. The high temperature generated during high speed machining facilitates the material plastification and, therefore, causes a tendency for more material side flow.

Chip Morphology. An increase in the nose radius increases the chip edge serration; the chip edge serration can be explained by the reduction in the actual chip thickness near the trailing edge. Since the chip formation takes place mainly along the nose radius, it is expected that the chip thickness varies along the cutting edge. Due to the nose radius, the chip thickness is decreased gradually to zero, causing high pressure at the trailing edge. Thus, the material at the trailing edge of the tool, where the chip thickness is a minimum, is subjected to high stress that causes tearing on the weakest edge of the chip. In addition, the variation in the chip velocity facilitates the non-uniform displacement along the chip width, which leads to chip edge serration. The existence of the chip edge serration facilitates trailing edge wear. Grooves are worn in the tool at the positions where the chip edge moves over the tool. These grooves deteriorate the surface roughness and, in turn, reduce the tool life.

The quality of surface plays a very important role in functionality of produced part. It is necessary to develop the methods, which can be used for the prediction of the surface roughness. According to those methods manufacturing engineers could set cutting machines without long-term adjusting. Material and time economy could be reached and also quality maintained. To describe the machined surface many parameters are used and even new parameters are introduced.

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