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Optimization of surface roughness in broaching

D. Fabre [a,b,*], C. Bonnet [b], J. Rech [a], T. Mabrouki [c,d]

[a] University of Lyon, ENISE, LTDS, CNRS UMR5513, 58 Rue Jean Parot, Saint-Etienne 42100, France
[b] AREVA NP SAS, Saint-Marcel 71380, France
[c] University of Lyon, INSA of Lyon, LAMCOS, CNRS UMR5259, Lyon 69000, France
[d] University of Tunis El Manar, ENIT, Tunis 1002, Tunisia

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ABSTRACT

The broaching process is used to generate high quality surfaces in very short times. In order to improve the understanding of the evolution of surface quality in broaching, a sensitivity study of the influence on the surface roughness of several broaching parameters dealing with the tool design, the cutting conditions or the workpiece material was performed. Forces and chip formation have also been analyzed so as to highlight the surface roughness generation. This paper shows how the process parameters (such as cutting speed or lubrication), tool design (rise per tooth, tooth angles, substrate material), and workpiece material affects the surface roughness.

Introduction

The broaching process is commonly used since the 19th century to generate complex and accurate surfaces in a limited time. Even if broaching is commonly used in aeronautical and automotive industries, a few researches have been achieved on this process compared with turning, milling or drilling processes.

The cutting forces and specific forces obtained in broaching applications have been well studied [1–3]. Those results are used to predict the broaching forces in an industrial context, depending on cutting tool geometries, process parameters and workpiece material. It can be used to design the cutting tool (main parameters of this tool are presented in Fig. 1) or the broaching machine, and smooth the forces variation in a broaching operation.

As broaching is used to finish functional surfaces, the impact of this process on surface integrity was also the subject of several studies. The influence of broaching on deformed layer thickness [4,5], on hardness [6,7] and residual stresses [8,9] has been analyzed.

Roughness is also a key quality criterion to take into account in high added-value sectors such as aeronautical or energy industries. An ANOVA achieved by Mo [10] on the impact of coolant, rake angle, cutting speed and rise per tooth (RPT usually noted h) showed that mean roughness (Ra) is more dependent on rake angle and coolant, and that cutting speed does not almost affect Ra. The maximum cutting speed studied was 10 m/min while new broaching applications usually raise this cutting speed up to 50 m/min.

Mean roughness value in broaching was also studied by Schulze on a fixed RPT value of 0.06 mm [8]. Obtained results show no significant variation of surface roughness when cutting speed varies from 7 to 50 m/min on a case hardening steel SAE 5120.

All these papers have investigated a limited number of parameters, in a limited range of value variation.

The case study presented in this work consists in the optimization of surface roughness in broaching of an X12Cr13 stainless steel with High Speed Steel (HSS) tool, and straight oil lubrication. The strategy of optimization is based on an end-user point-of-view (Fig. 2). When facing a poor surface roughness after broaching, what is the easiest parameter to vary? The cutting speed is the single parameter that can be modified when the machine, the tool and the lubrication have been selected. That is why the influence of cutting speed has been investigated first in this research work.

Then if the optimization induced by the change of cutting speed is not satisfying for the end user, the design of another cutting tool can be considered by varying the rise-per-tooth, the rake angle, the flank angle, the substrate, the coating, etc. Of course this is more costly (some k€) and time consuming as end-users have to wait several weeks for the delivery of the new tool. So in order to make the right design quickly, we have investigated broach parameters.

Then, if the new broach is not fully satisfactory in terms of generated surface roughness, it is possible to modify the lubricant. This is always an uncertain work, since it is very difficult to know the composition of lubricants available on the market. Even if the composition is well known, the interaction between their components, the workpiece and cutting tool materials is hardly

* Corresponding author at: University of Lyon, ENISE, LTDS, CNRS UMR5513, 58 Rue Jean Parot, Saint-Etienne 42100, France.
E-mail address: fabre.dorian@gmail.com (D. Fabre).

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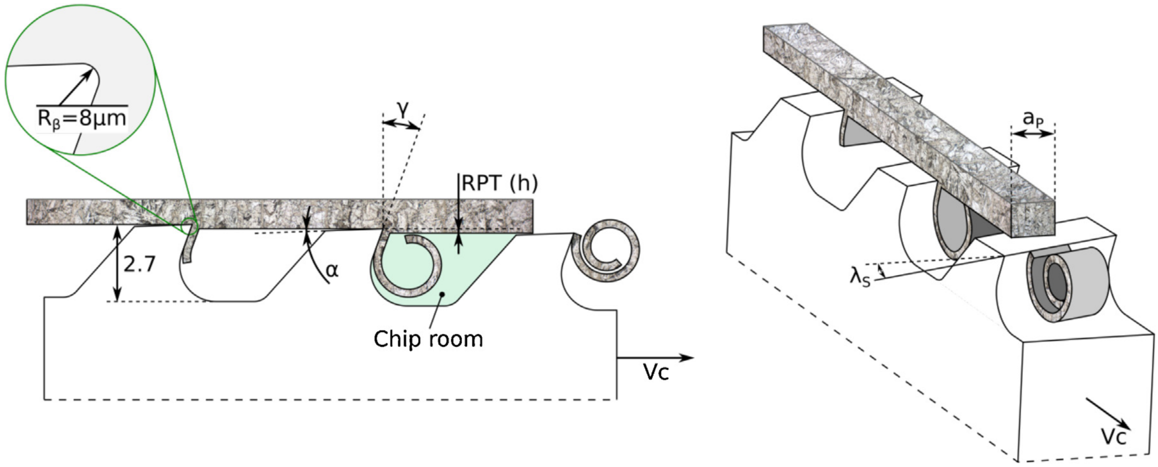

Fig. 1. Schematic representation of broaching parameters.

predictable. Moreover, it is also a tough work since the new oil has to be validated by the machine builder and the health authority of the company, which is a long and expensive procedure. So a sensitivity study on a large number of lubricants has been made in order to evaluate the interest of this solution to improve surface roughness.

At this point, if the modification of lubricant is not satisfactory, the stiffness of the clamping system and of the whole machine can be investigated. The redesign of the mechanical structure is also a long and costly problem. This parameter has not been investigated in this work.

Finally, the last solution consists in modifying the material of the workpiece. This is also a very complex task since it has to be discussed with the designer of the part. This is only possible if the potential financial gain is substantial and if a large number of parts are planned to be produced. So, it has been decided to investigate the sensitivity to the workpiece material.

The structure of the study is presented in Fig. 2.

Note that the influence of the machine structure was not properly studied in this work, even if its influence can be observed on some broaching tests as discussed below.

Experimental setup

The experimental setup developed for this study is presented in Fig. 3. A 4 axis machining center with a horizontal spindle was exploited to carry out broaching experiments. The spindle was equipped with a specially designed workpiece holder, and a clamping system mounted on a 6 axis dynamometer maintains the broaching tool. In order to limit the disturbances induced by the entry/exit of broaching tool teeth, tests were carried out with a single tooth cutting tool.

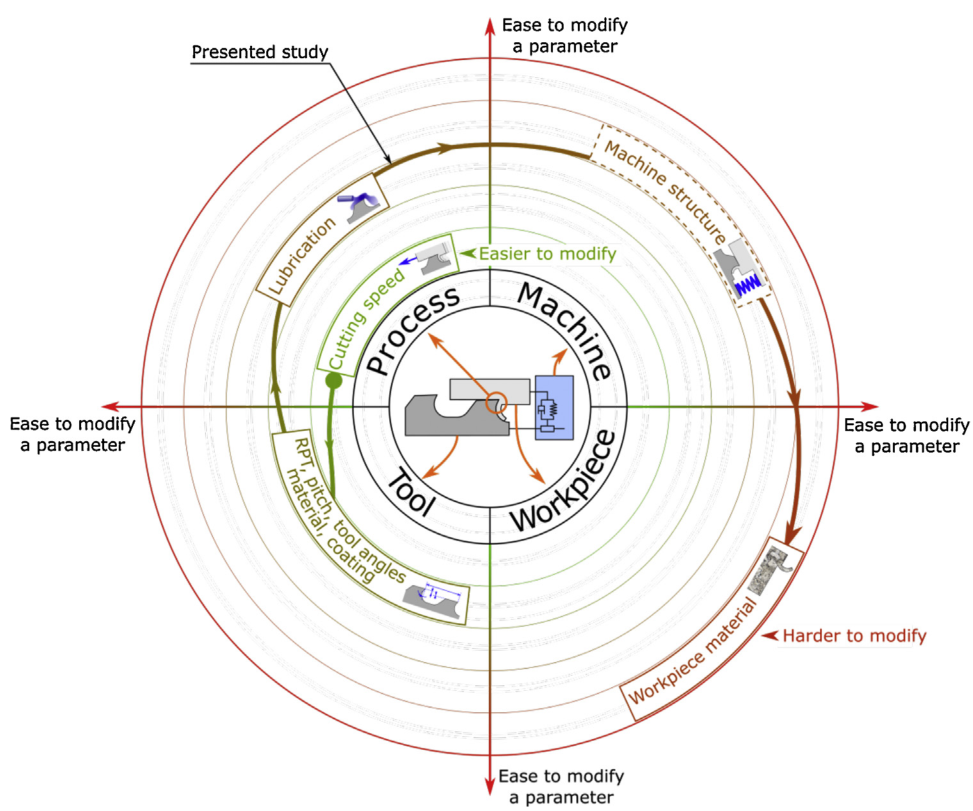

Fig. 2. Study of surface roughness; from the easier to the harder modifiable parameter.

II. EXPERIMENTAL SETUP

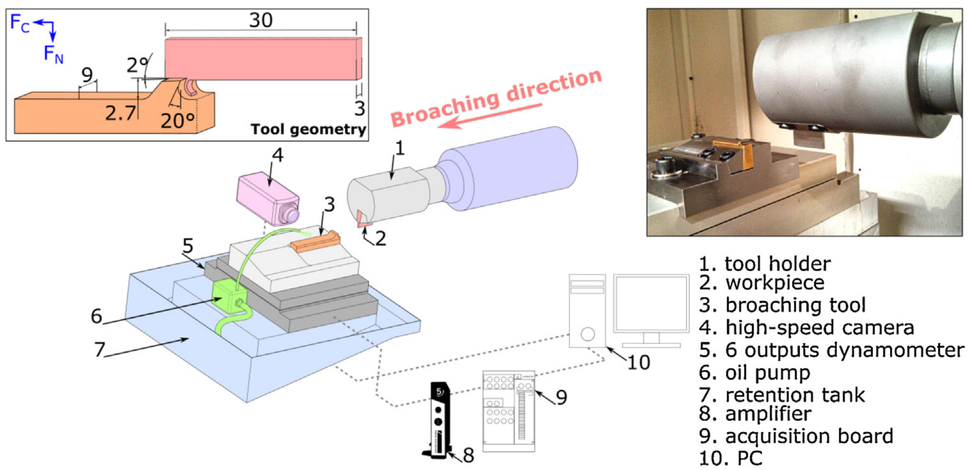

Fig. 3. Experimental setup with a single tooth.

Note that an external broaching setup is developed and used in this document as a way to reproduce the cutting mechanisms observed in an internal broaching operation. It is then possible to observe the mechanisms occurring in the cutting zone, and to measure the cutting as well as the normal forces.

The study of forces evolution and chip morphology concerns the broaching of X12Cr13 stainless steel workpiece with HSS M35 tool TiN-coated on flank face only. This X12Cr13 steel is a mainly martensitic stainless steel with some ferritic grains. The structure is made of lamellas due to rolling process. Those lamellas are oriented perpendicularly to the broaching direction as presented in Fig. 4.

The same reference straight oil is used in this study, except when the influence of lubrication is observed. This oil is specifically designed for broaching applications and is delivered through a pump with a volume flow of about 400 l/h.

Note that all tests were replicated five times; the error bars presented in the following curves are obtained through a Student law with a 0.9 cumulative probability. After broaching operations, chips have been collected and analyzed. The presented mean arithmetic roughness *Ra* is measured with a cut-off of 0.8 mm with a Gaussian filtering.

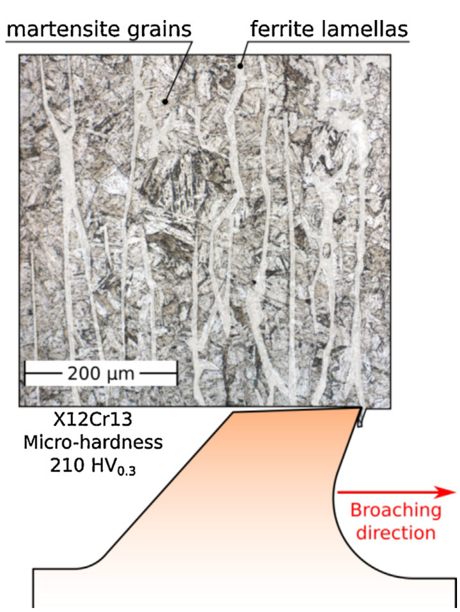

Fig. 4. X12Cr13 microstructure, hardness and broaching direction.

Influence of cutting speed (V_c)

In usual broaching applications, cutting speed can easily be varied by the broaching operator as presented in Fig. 2. Current cutting speed values are usually very low (below 5 m/min), as tool material is often High Speed Steel (HSS). For specific applications using high machinability alloys, cutting speed can reach values up to 50 m/min. The influence of this speed on broaching forces and chip formation is discussed here.

Fig. 5a shows that the surface roughness parameter *Ra* is decreased up to more than 5 times when cutting speed is raised from 2.5 to 50 m/min. Note that even if mean roughness is improved with the increase of cutting speed, more height variation appears with high cutting speeds. This can be attributed to stiffness properties of the cutting tooth and of the global experimental setup. Finally the increase of cutting speed significantly improves roughness, but has a negative effect on macroscopic surface geometry and flatness as observed in Fig. 5a.

The observation of a cross section obtained with low cutting speed reveals the formation of dimples, probably due to the formation and deposition of built-up edge on the generated surface.

If the force curves presented in Fig. 5c and d are considered, it is possible to identify 6 specific points *t0* to *t5*, observed in all the 5 tests carried out in the same conditions. Those observations were carried out thanks to observations of chip formation made on the experimental setup equipped with a camera.

- *t0* → *t1*: The chip formation is initializing. During this period, the chip root is not curled-up, the workpiece material is more pushed forward than properly cut. This phenomenon was experimentally and numerically observed by Zanger [11], who evoked a necessary time to initialize chip formation, and stabilize shear plane angle.
- *t1* → *t2*: At *t1*, the embryonic chip begins to rotate around its root, until the proper cutting begins at *t2*. The stiffness of the setup is stabilized at *t2*, and the chip starts to grow.
- *t2* → *t3*: This step corresponds to the period *P1* in the previous chapter. The chip grows properly until the stabilization of the contact length.
- *t3* → *t4*: A rotation of the chip can be observed at *t3*. The chip is then rotating toward the uncut surface of the workpiece.
- *t4*: The chip hits the uncut surface. At this step the chip stops its rotation and its formation is now parallel to the rake face. This tends to increase its shear angle and apply a force on chip

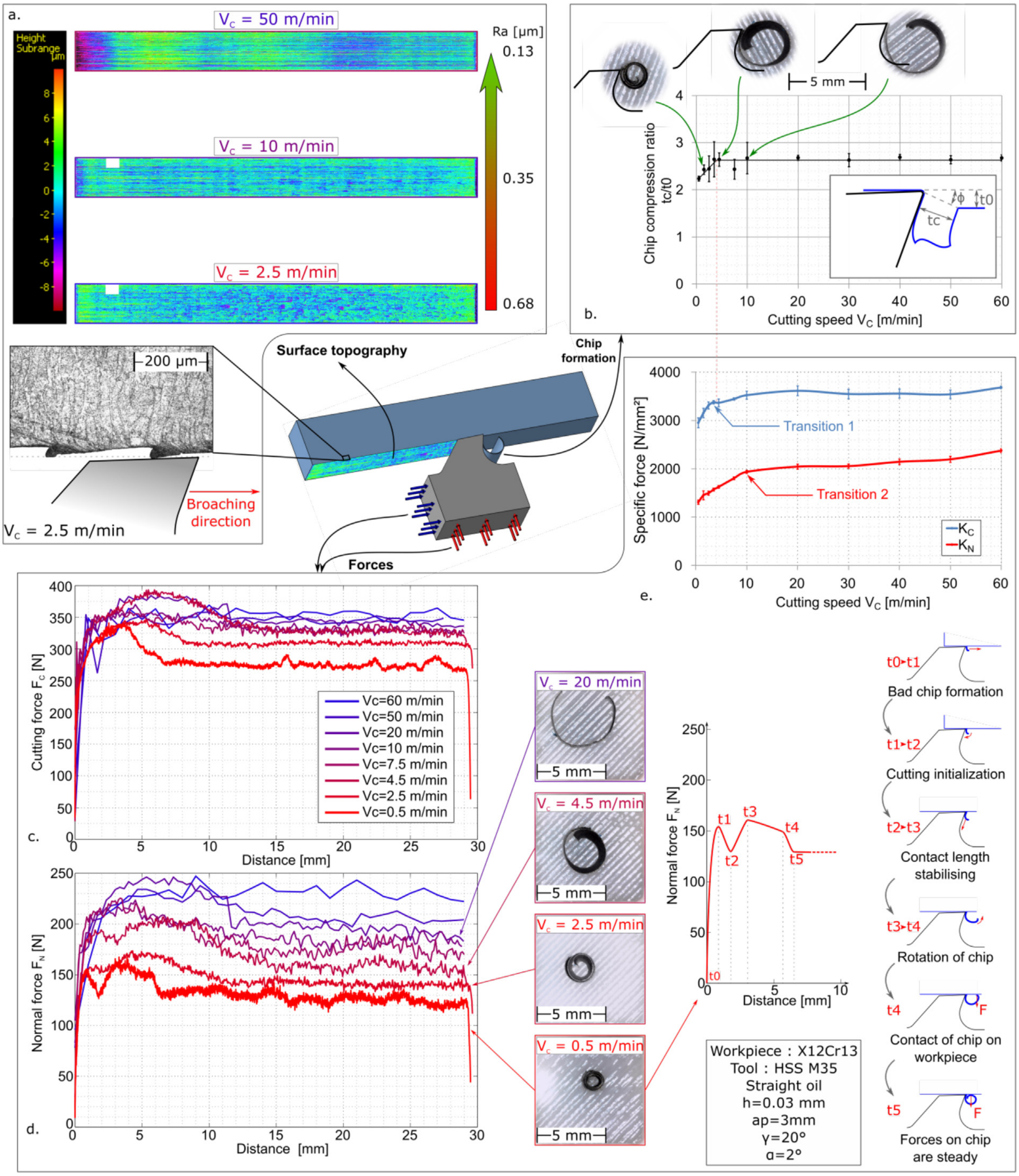

Fig. 5. Surface topography, forces and chip formation variations as functions of cutting speed.

oriented in the same direction as normal force. Chip evacuation is easier thanks to this force and normal force decreases.

- *t5*: At this point the chip ends its first round. The extremity of the chip hits the chip itself. From this step, there is no major modification in the chip formation mechanisms; forces involved in the process are steady.

Now focusing on the stabilized part of the force curves (measured after *t5*), it is possible to identify the specific cutting forces presented in Eqs. (1) and (2). An increase in specific forces with the raise of cutting speed (see Fig. 5e) is observed, whereas the increase of cutting speed usually results in the decrease of cutting and normal forces in machining processes.

Note that specific force corresponds to the energy efficiency of a process as it is expressed in N/mm^2 or J/m^3.

$$K_C = \frac{F_C}{h \times W_W} \quad (1)$$

$$K_N = \frac{F_N}{h \times W_W} \quad (2)$$

Fig. 5e highlights two transition zones. The first one is observed on specific force K_C for a cutting speed of 5 m/min. A similar characteristic point can be observed on chip compression ratio. Under 5 m/min, the chip is tightly curled-up, and can easily fit in the chip room as presented in Fig. 5b. From 5 m/min, chip curl-up diameter is greater than the tooth height; the chip/tool contact length is then always the same.

Note that the force applied by the uncut surface on chip probably results in a torque on the chip root, that helps its formation and evacuation.

A second less important transition point is highlighted on specific force K_N. The observation of chip revealed that below 10 m/min, the chip always hit the uncut surface during the process, while this contact disappear for cutting speed over 10 m/min. From 10 m/min, chip always looks like the one presented in Fig. 5d for V_C = 20 m/min.

The cutting speed usually reaches values up to 10 m/min in industrial applications with HSS tools. In the study presented in this document, the reference cutting speed is limited to 2.5 m/min to maintain good cutting conditions, adapted to the broaching of the X12Cr13 stainless steel.

Influence of cutting tool parameters

If the cutting speed is very easy and quick to modify even during the broaching process, the second level for action usually deals with tool characteristics. Its geometry, material and coating composition or manufacturing quality can have a significant influence on the surface quality of the generated surfaces.

*Influence of rise per tooth (*h*)*

Rise per tooth (similar to feed in conventional cutting processes) is fixed during the tool manufacturing and cannot be easily varied during the cutting operation as in turning. Nevertheless, modifying the tool design is a current and simple method used to improve the broaching performances, and usually results in the modification of the RPT evolution along the industrial broaching tool.

In the following, an overview of the impact of RPT in relationship with chip formation and broaching forces characteristic curves is presented.

Fig. 6a shows the mean roughness values *Ra* as a function of RPT. An increase of RPT from 0.01 to 0.06 mm induces an increase by slightly less than 5 times the mean roughness values. The qualitative observation of surface topography also gives us information on the cutting mechanisms. With low RPT the surface is smooth, no macroscopic bulks or dimples are generated. When increasing RPT values, random dimples are created on the surface as presented in the micrograph of Fig. 5a. This can be attributed to the alternative formation and deposition of built-up edges on the surface due to high adhesion between workpiece and tool materials near the cutting edge.

The individual study of forces curves gives information on chip formation (Fig. 6b) and process stability (Fig. 6f). Forces are also increased with the raise of RPT as presented in Fig. 6c and 6e, even if the specific forces tend to be lessened (see Fig. 6f).

The increase of RPT has a direct impact on chip formation as its curl-up diameter is significantly increased. Chip compression ratio is not seriously affected by the variation of RPT even if a low point can be identified for a RPT around 0.03 mm.

Seven periods with a specific chip formation behavior has been identified (Fig. 6d).

- *P0*: Beginning of chip formation according to the same phenomenon described in the period $t0 \rightarrow t1$ in the previous section. Normal force curves corresponding to RPT below 0.05 mm are greater than the one observed for RPT over this value in this zone. This can be attributed to a brief ploughing phenomenon during the stabilizing of forces with low RPT. This phenomenon is not observed for higher RPT values which enable a faster stabilizing of chip formation.
- *P1*: Beginning of proper chip formation, the contact length L_C is stabilizing and the balance of forces is being established. The effects of the setup stiffness can be observed in this zone as well as in the previous one, as chip thickness is also stabilizing. Note that both cutting and normal forces tend to rise during this period.
- *P2*: The contact length is stable.
- *P3*: The chip enters in contact with the bottom of the chip room, and is pressed on the rake face. This tends to increase the shear angle, and drop cutting forces. Note that with high RPT, this zone can be composed of a second peak value. This occurs when the grinding wheel achieving the rake face gets beneath the theoretical bottom of the chip room. This can cause the blocking of chip during its formation when its thickness is too important and limits its curvature.
- *P4*: During this period, there is no contact between the chip and the bottom of the chip room. The chip is generated freely. The chip enters in contact with the workpiece which has no effect on forces.
- *P5*: While in contact with the workpiece, the chip is deformed. The initiation of *P5* zone is due to the intense stresses of the chip that is not able to be evacuated causing cutting and normal forces to increase. If this zone cannot be observed, it means that the chip formation is never constrained, and the chip can always be generated freely (it curls-up efficiently).
- *P6*: When the increase of these forces reaches a limit value, a slight rotation of the chip around chip root occurs and releases the chip. If this rotation is not possible, the chip can break as observed on the test carried out for h = 0.08 mm or h = 0.09 mm (Fig. 6e).
- *P7*: The same cutting mechanisms as observed in the part *P4* are identified here, explaining the similar forces level on *P4* and *P7*. If the chip was broken as presented for h = 0.08 mm in Fig. 6e, a second peak can be observed on *P7* for the same reason as the one presented on period *P6*. As the chip was broken and thus shorter, the time between the two peaks is the time needed for the chip to contact again the workpiece. In other words, the second peak value in period *P7* can only be observed if the chip has broken.

Based on the tool–material-pair method (TMP) defined by the French standard NF66-520, a minimal RPT around 0.03 mm has been highlighted (Fig. 6f). This method is based on the analysis of the specific force when varying a cutting parameter. A high specific force and/or a rapid variation of the slop reveal problems during chip formation. This minimal value of 0.03 mm is fixed in the next paragraph while the cutting speed is varied.

In order to study other process parameters while taking into account the previously studied conditions, a matrix of tests is fixed including 3 values of h (0.01, 0.03 and 0.06 mm) and 3 values of V_C (2.5, 10 and 50 m/min). Each cutting condition thus requires the achievement of 9 tests point for one specific cutting condition. The forces presented for a single condition point correspond to the average force measured on the period *P4* of Fig. 6c and 6e.

Influence of cutting tool angles

In broaching applications cutting angles such as rake angle γ, clearance angle α or edge inclination angle λ_S can influence the chip formation mechanisms and have an impact on the evolution of forces or directly on the surface quality. The study of the influence of those parameters is presented in the following section.

Influence of rake angle γ

In Fig. 7, rake angle was varied as 15°, 20° and 25°.

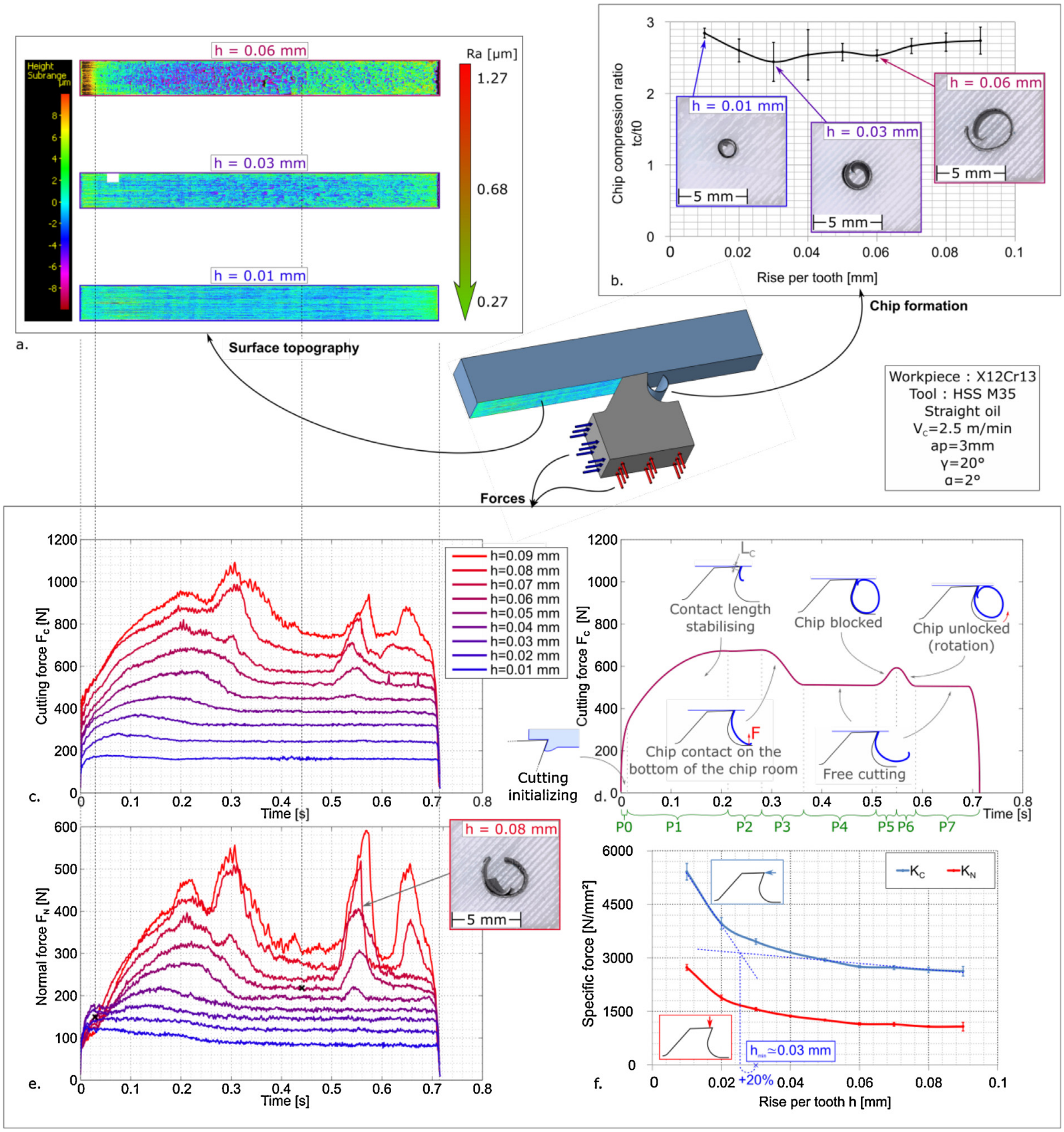

Fig. 6. Surface topography, forces and chip formation variations as a function of RPT.

The worst surface roughness *Ra* is observed for high RPT and low cutting speed; decreasing RPT or increasing the cutting speed improve the mean roughness of the surface. *Ra* observed for $\gamma = 15^{\circ}$ varies from 0.14 µm in the better conditions to 2.91 µm in the worst ones.

For high RPT, it can be assumed that increasing the rake angle reduces the plastic strain on the primary shear zone, and consequently the specific forces. A different behavior is observed for low rise per tooth value of 0.01 mm where specific forces for $\gamma = 15^{\circ}$ are lower than the one observed for $\gamma = 20^{\circ}$.

This change in cutting pressure tendencies can be attributed to chip geometry. As previously observed a tightly curled-up chip has a positive effects on both cutting and normal forces, what explains the lower cutting pressure for $h = 0.01$ mm with $\gamma = 15^{\circ}$ than with $\gamma = 20^{\circ}$. This particular chip geometry is presented in Fig. 7d.

It can be underlined that the tooth strength has to be considered along with the previous observations while designing tool teeth; an increase of rake angle lowers the ability of the tooth to support broaching forces, as well as its stiffness.

Influence of clearance angle

In broaching, teeth with low clearance angle usually between 1° and 2° are used. Reducing clearance angle leads to more friction between workpiece surface and clearance face, what cause a raise in normal and cutting forces. This behavior is presented in Fig. 8a. The same reduction on cutting and normal forces with clearance angle decreasing was observed by Oliaei [12].

From industrial point of view, finish broaching teeth can be designed with low clearance angles, usually around 1°. This may reduce surface roughness under low cutting speed of 2.5 m/min as shown in Fig. 8b. The improvement of mean roughness with the decrease of clearance angle can be attributed to a phenomenon similar to burnishing.

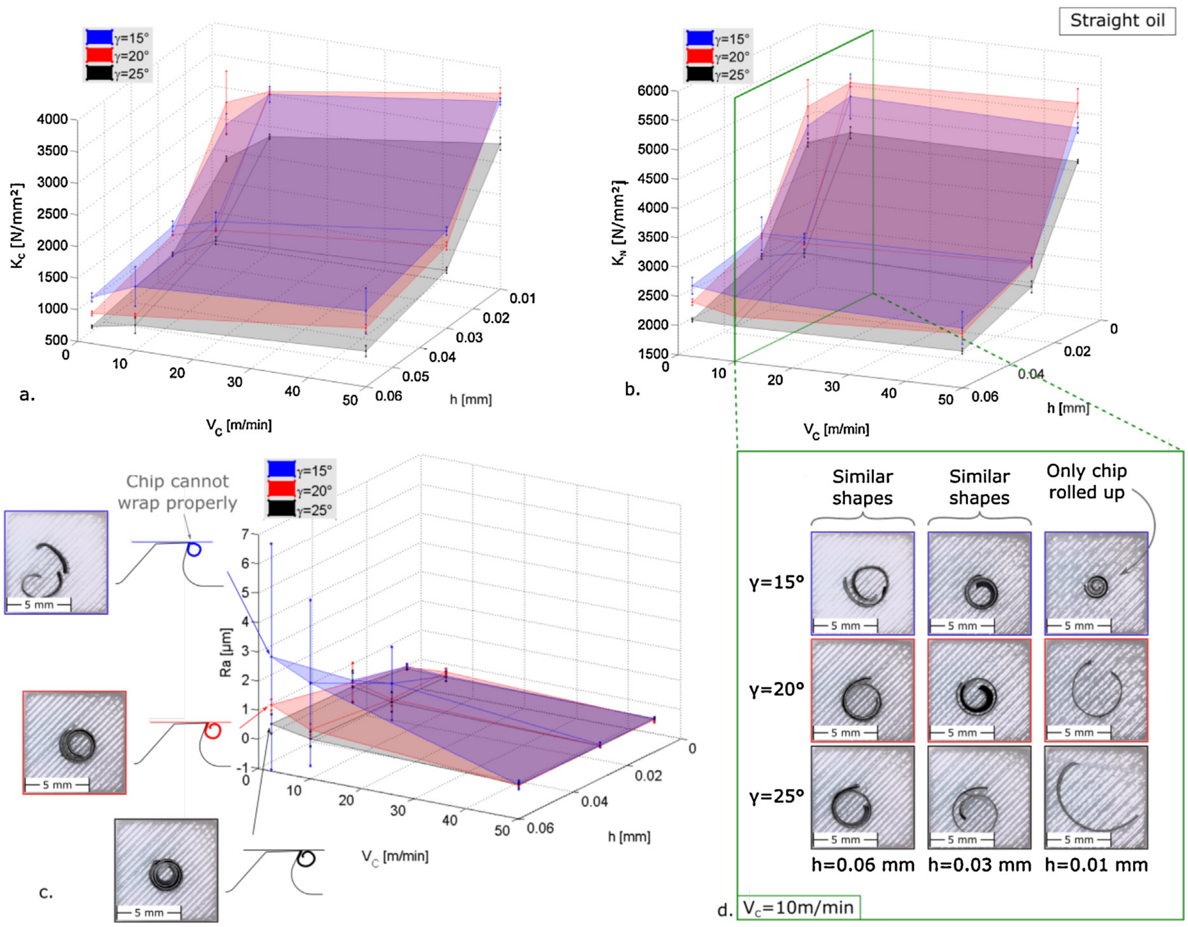

Fig. 7. Impact of rake angle on specific forces, roughness and chip curl-up.

Influence of edge inclination angle

If rake angle variation has an impact on chip curl-up diameter and the evolution of broaching forces, applying an edge inclination angle may modify chip contact with uncut surface. The force applied by the uncut surface on chip will consequently be modified. In order to evaluate the sensitivity of broaching output on this angle, an oblique cutting operation with $\lambda_S = 15^\circ$ was compared to standard orthogonal cutting. Obtained results are shown in Fig. 9.

First of all, the dispersion of measures of *Ra* in oblique cutting tends to be more important than the one observed in orthogonal (Fig. 9a). This can be attributed to a loss of stiffness of the setup when introducing a third force component due to edge inclination angle.

No improvement of surface roughness was observed with the introduction of an orientation angle, the mean roughness values appears to be equals or worse in oblique than in orthogonal cutting (Fig. 9a).

Most of the specific forces are identical regardless of the cutting conditions, except the tests achieved with a very low cutting speed and low rise per tooth. In those conditions, the cutting and normal forces observed in oblique broaching are higher than the one measured in orthogonal tests (Fig. 9c and 9d). As chip curl-up diameter is similar in oblique and orthogonal cutting in those

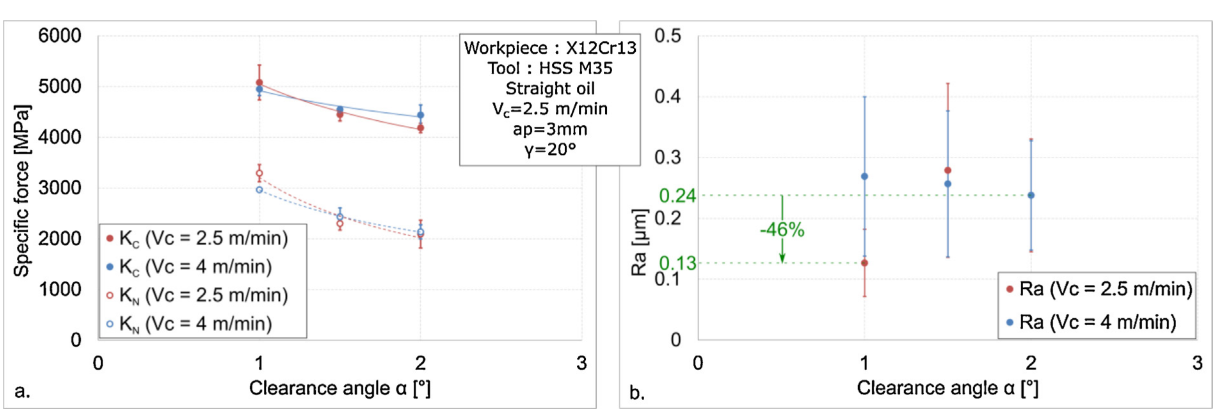

Fig. 8. Specific forces as a function of clearance angle.

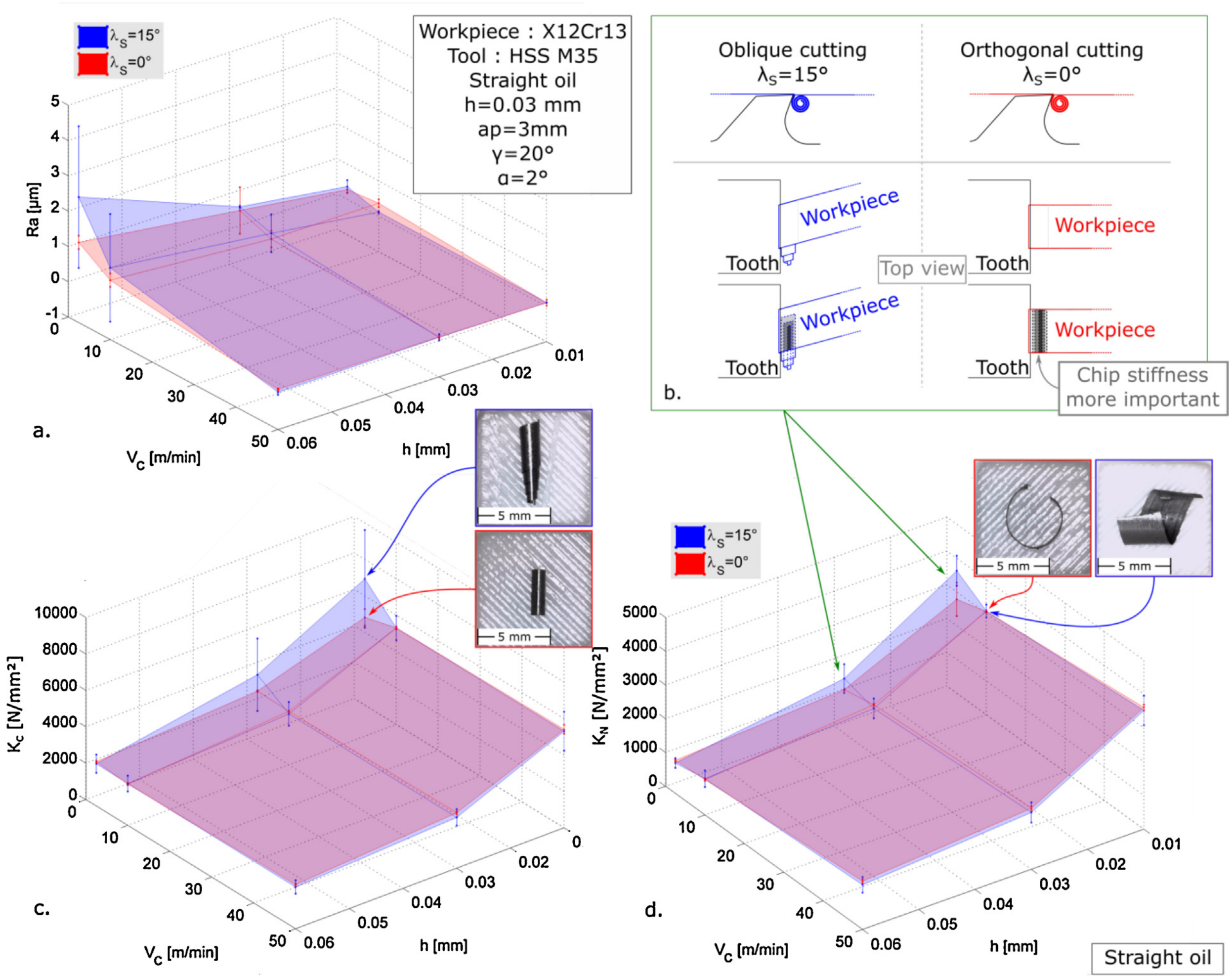

Fig. 9. Impact of oblique cutting on specific forces and arithmetic roughness.

conditions, this increase of force observed on oblique cutting can be attributed to a loss of stiffness of the chip in oblique cutting due to the orientation angle reproduced on the chip, as presented in Fig. 9b.

Influence of tool substrate

Another parameter that may significantly influence the quality resulting of cutting processes is the substrate of the tool, even more if the tool is not coated on the rake face as in most of broaching applications. In this section, the comparison between the results obtained with HSS M35 and carbide H10F substrate are presented. Note that HSS tool is coated on the flank face only while the carbide tool is uncoated.

Fig. 10a and 10b shows that carbide tools are responsible for less cutting and normal forces in most cases, except for the cutting conditions with higher RPT and lower cutting speeds, in which the cutting pressures are similar with carbide and HSS tools.

The surface roughness parameter *Ra* is not depending on the cutting tool substrate as presented in Fig. 10c.

The use of carbide tools will allow a decrease of forces but will have no influence on surface roughness. Note that carbide tools are more complex and expensive, and are also less ductile. Those properties can prevent their use in some applications performed with long and thin broaching tools, more sensible to breakages due to flexion.

Influence of lubrication

The previously studied parameters are quite quick and cheap to modify in an industrial point of view. Modifying the lubrication method can in the contrary be time-consuming (as adaptation on the machine could have to be operated, or for the formulation of new oil composition), and changing a huge quantity of oil can be expensive. Nevertheless, the lubrication method as well as the lubricant composition can significantly influence the contact properties between the tool and the workpiece, and consequently influence the generated surface roughness.

Influence of lubrication method

The lubrication method plays a key role in the decrease of friction coefficient, and can also be selected for its thermal effects or its ability to evacuate chips. Fig. 11 presents the comparison between dry conditions, emulsion (with 5% straight oil) and straight oil. Note that a constant emulsion flow is provided to the cutting area during the cutting tests, as only one opened cutting tooth is used for the tests.

Note that oil is here simply applied with a brush before tests; oil flow has no mechanical chip evacuation effects.

Dry tests are responsible for the worst roughness values, and the highest specific forces. This can be attributed to high friction coefficients between HSS and the stainless steel composing the

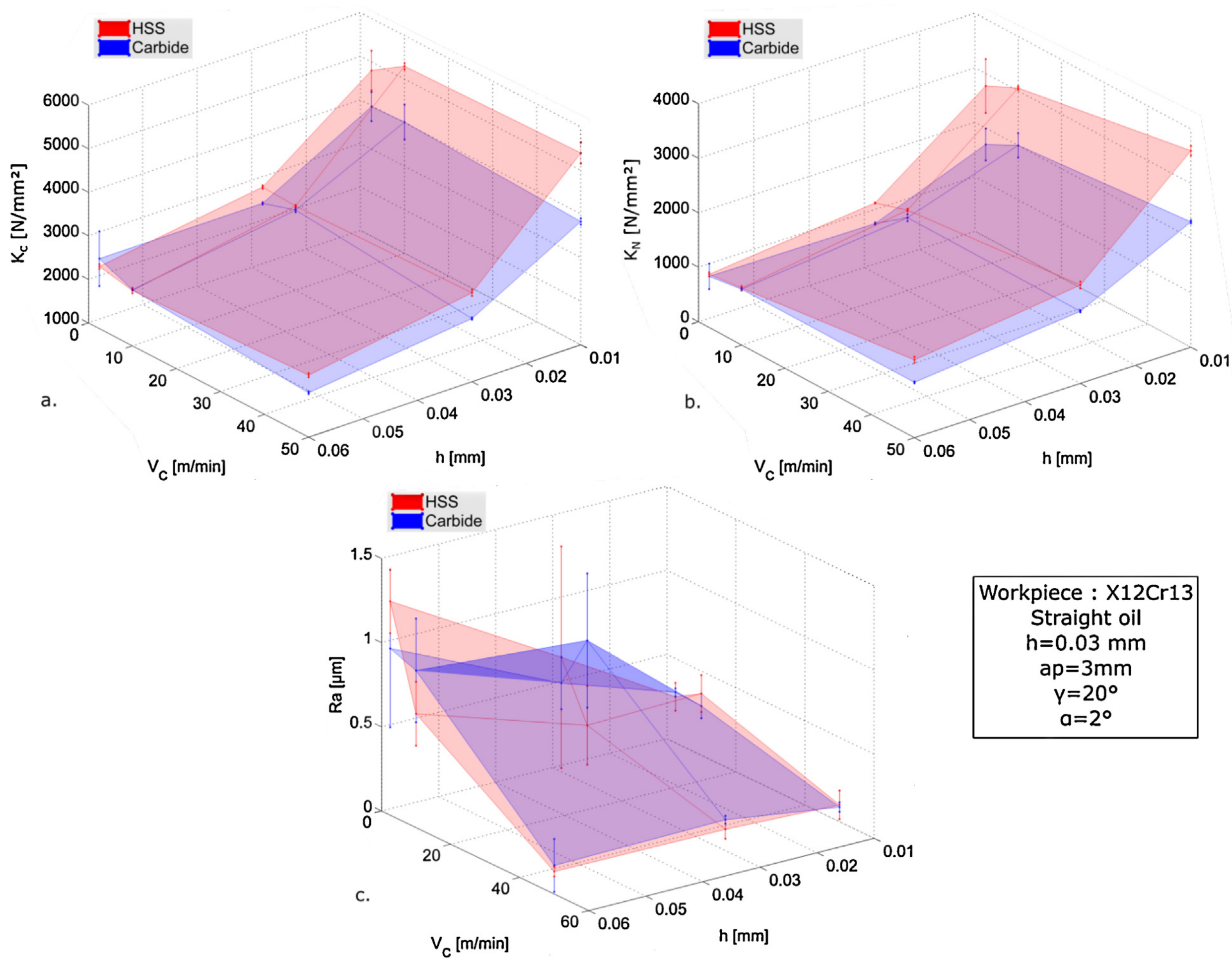

Fig. 10. Influence of cutting tool substrate on specific forces (a and b) and arithmetic roughness (c).

workpiece under dry conditions. The better mean roughness is observed with straight oil tests under the most critical conditions (high RPT, low cutting speed). This can be attributed to very low friction coefficient with the use of straight oil [13].

A relationship between specific forces and chip curl-up is highlighted in Fig. 11b. As previously observed, decreasing the chip curl-up diameter tends to decrease specific forces, that is why specific forces are less important under straight oil with high RPT, while they are less important under emulsion with very low RPT. The increase in cutting speed has positive effects on roughness even for dry tests, highlighting the positive effects of thermal softening on roughness.

Influence of straight oil composition

As broaching is mainly conducted under straight oil because of the good results obtained on roughness, a comparative study of several cutting oils produced by 4 different oil suppliers has been achieved.

Some properties of these oils are presented in Table 1.

Fig. 12 corresponds to the evolution of both cut surface roughness *Ra* and specific cutting pressure K_C according to 10 different lubricant grades and 2 cutting speeds. Based on this figure, it can be shown that *Ra* is significantly influenced by the oil tested, and a variation up to 100% between the better and the worst straight oil is highlighted. A reduced influence of cutting oil grade on specific cutting pressure in cutting direction is shown, as well as a slightly more important influence on normal direction.

As tests presented here were carried out at low cutting speed, the effects of heat generation are neglected. Moreover, straight oil can significantly reduce friction coefficient and consequently heat generation compared with dry cutting tests, even if straight oil has poor heat transfer coefficients. Claudin showed that applying straight oil results in falling friction coefficient, but has no effect on the heat percentage transmitted to a pin on a tribometer setup [13].

In the presented tests, varying the composition of straight oils mainly impacts friction coefficient, and may have a reduced effect on heat generation.

Influence of Workpiece material

In the production of high added-value parts, the workpiece material is usually selected for its physical and mechanical properties corresponding to a specific application. The machinability of the part is often a secondary problem that is not significantly taken into account in the choice of the material composition. Then modifying the workpiece material for machinability reasons is rare or even not possible.

The reference and previously studied material is an X12Cr13 ferritic–martensitic stainless steel. The optical observations of the surface obtained after broaching highlighted the apparition of asperities as observed in Fig. 5a. A nickel electroplating is achieved on the broached surface in order to trap the surface asperities before polishing in the cross-section, and limit the border effects induced by polishing.

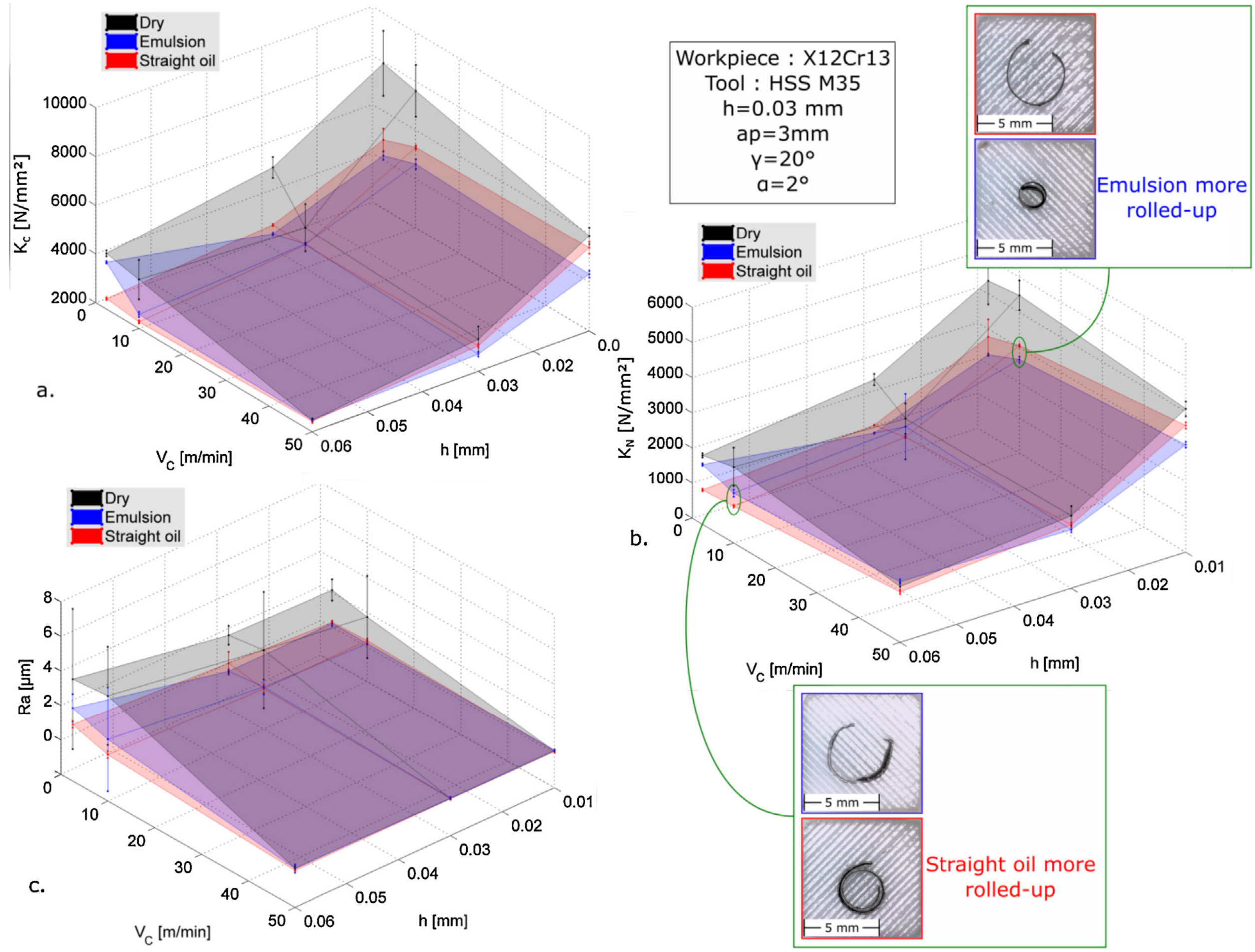

Fig. 11. Influence of lubrication method on specific forces (a and b) and arithmetic roughness (c).

It was then possible to observe the formation of oriented dimples as presented in Fig. 13. In order to identify if the apparition of dimples is due to the ferrite or martensite phase, we performed similar tests on a pure ferritic stainless steel (X6Cr17) as well as on a pure martensitic one (15-5 PH). In those conditions, dimples are only generated for ferritic–martensitic dual phase steel, and not for both pure ferritic and pure martensitic steels as presented in Fig. 13.

This dimple formation was observed by Simoneau in micro-machining applications of ferrite–pearlite steels [14]. He assumed that dimple formation is the result of steel dual phases, and observed that dimples are always initiating at a ferrite–pearlite boundary. In further numerical work, Simoneau observed that this dimple appears when the cutting edge is moving from a hard grain to a softer one [15].

In our case study, the influence of the transition between harder and softer material introduced by Simoneau may partially explains the apparition of dimples under very low rise per tooth of 0.01 mm. But the pitch between dimples is more important for high rise per tooth of 0.06 mm (as well as the height of the dimples), and in those conditions the cutting edge has to cut through several martensite–ferrite boundaries before being deposited on the surface, it is not directly linked to the alternation of ferrite and martensite phases. In those particularly unfavorable conditions, dimples are followed by prow due to the adhesion of chip on clearance face.

As presented in Fig. 14c, the workpiece material composition has a direct impact on surface roughness. The apparition of dimples for X12Cr13 leads to *Ra* up to 3 times greater than the ones observed while broaching single-phase steels in low speed and

Table 1
Properties of straight oil tested.

Oil	Supplier	Cinematic viscosity at 40 °C (cst)	Sulfur content (%)	Chemistry
Reference oil	1	30	2.874	Mineral base
Oil 1	2	50	50	Pure additive
Oil 2	2	112	35	Synthetic with additives
Oil 3	2	32	2.3	Mineral base
Oil 4	3	42	0.156	Vegetal base
Oil 5	3	20.5	4	Mineral base
Oil 6	4	40	<0.1	Vegetal base
Oil 7	4	17	3.1	Mineral base
Oil 8	4	68	14	Mineral base
Oil 9	4	39	1.89	Vegetal base

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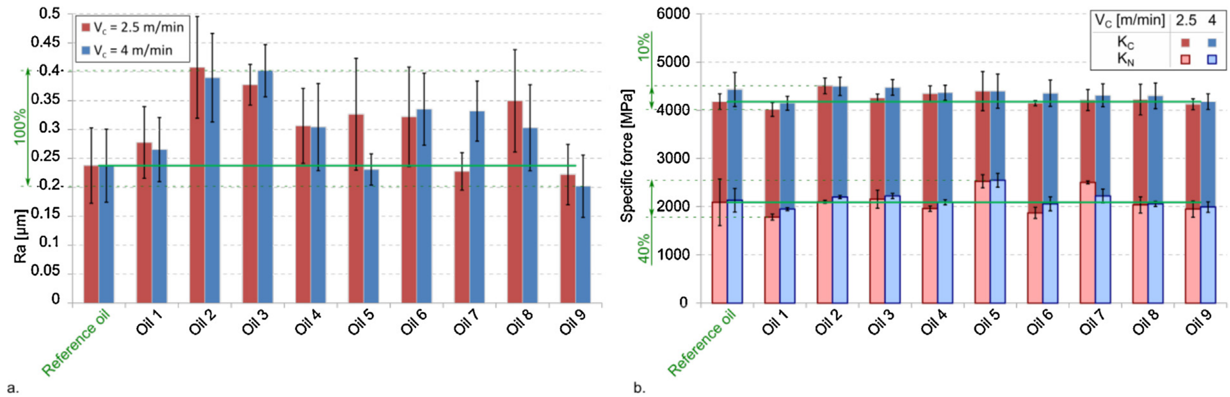

Fig. 12. Influence of straight cutting oil choice.

high rise per tooth conditions. Note that *Ra* observed for both pure martensitic and ferritic steels are substantially similar, which means that roughness value is mainly dependent on dimples apparition. If the focus is made on roughness values obtained for a $V_C = 2.5$ m/min and $h = 0.01$ mm, *Ra* values obtained while broaching a dual-phase material are 3 times higher than the ones obtained for a single-phase material.

Finally, the apparition of dimples on the X12Cr13 stainless steel is probably due to several phenomena. The first one highlighted by Simoneau is the alternation of phases with different mechanical properties. It can also be assumed that tribo-chemical phenomena occurring at the tool–workpiece interface are responsible for material welding and sticking on the tool, resulting in built-up edge formation and deposition. The setup stiffness also partially plays a role in the deposition of this built-up edge. The use of carbon free steel as tool material can be studied as a way to limit those phenomena, as presented by Klocke [16].

Broaching pure martensitic steels results in higher cutting pressures in both cutting and normal directions compared with X12Cr13, probably due to higher mechanical properties of martensite. Close values of cutting pressures are observed while broaching pure ferrite or ferrite–martensite stainless steels.

Discussion

In this research work, a lot of parameters in relation with the process, the tool, or the workpiece were varied from the simpler to modify in an industrial point of view, to the harder one (Fig. 2).

The cutting speed was then the first studied parameter. The increase of cutting speed has shown significant positive effects on the surface roughness. Higher cutting speeds result in more thermal softening effects on the workpiece material which tends to reduce the workpiece material mechanical properties as well as the friction coefficient at the tool/workpiece interface [17]. While in main cutting applications the cutting force tends to decrease with the increase of cutting speed as presented in the tool–material pairing method defined by the French standard NF66-520, an opposite behavior was highlighted in this work. This was attributed to chip formation as the same evolution trend was

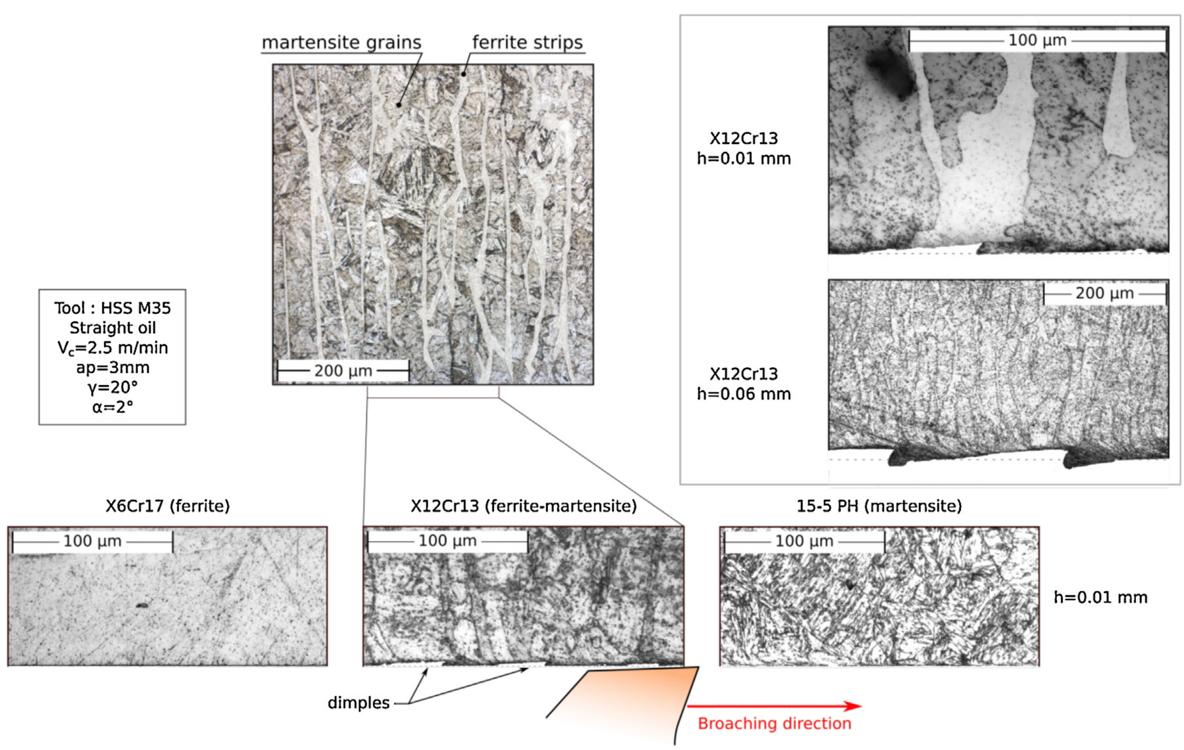

Fig. 13. Observation of a cross section of a broached surface for pure ferrite (X6Cr17), pure martensite (15-5 PH) and ferrite–martensite (X12Cr13) stainless steels.

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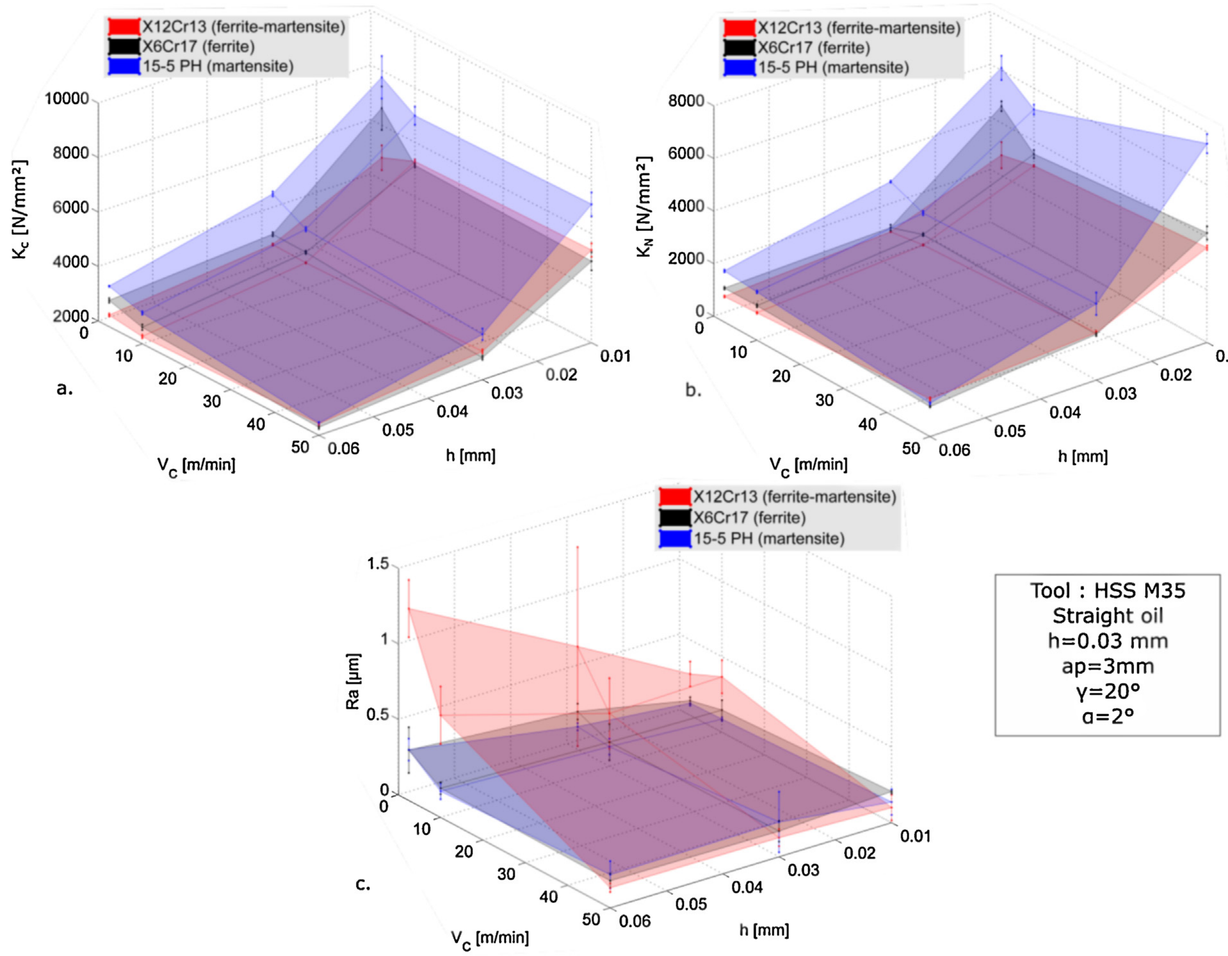

Fig. 14. Influence of workpiece material on specific forces (a and b) and arithmetic roughness (c).

observed on cutting pressure evolution and chip compression ratio (Fig. 5).

Then, the design of the cutting tool was varied as this is usually the second level of action in broaching process. RPT, cutting angles or substrate material variation was studied.

As RPT values are directly linked to the cutting and normal forces with Eqs. (1) and (2), using small RPT values result in reduced forces values applied on the cutting tool and consequently to the whole setup. Reducing the force applied on the tool results in less influence of the stiffness of this setup, the strain of this setup is then negligible and the cutting is more stable which also has a positive effect on surface roughness, reducing waves formation. Note that if the machine structure was not properly studied in this work, its influence was observed on the surface topography.

The increase of rake angle tends to reduce the cutting and normal forces, if the effects of chip are neglected. A decrease of the resulting plastic strain in the primary shear zone can explain this decrease in cutting forces. As evocated previously, this decrease of cutting force may result in a reduced effect of the setup stiffness, particularly significant with low cutting speeds and high RPT. This explains the gap of surface roughness observed in those conditions between rake angles of 15° and 25° (Fig. 7c).

The influence of clearance angle can be attributed to a burnishing effect. When the cutting speed reaches a particular level allowing a stable cutting (between 2.5 and 4 m/min), using a low clearance angle of 1° can reduce significantly the surface roughness parameter values *Ra* (Fig. 8b). The increase of the friction zone between the clearance face and the workpiece is then favorable when considering surface roughness.

The cutting tool substrate has shown no significant influence on the surface roughness evolution, even cutting pressures observed with carbide tools are lower than the ones observed with HSS substrate. This can be attributed to more chemical affinities between X12Cr13 stainless steel and HSS than with carbide.

When the previous parameters are fully optimized, it is possible to modify the lubrication method or the lubricant composition. This can be complex to implement industrially but should be considered as an efficient way to improve the surface roughness of the generated surfaces. High differences of roughness values were then observed between dry, emulsion and straight oil broaching tests. While broaching under dry conditions shows very high forces level (Fig. 11a and b) and bad surface roughness (Fig. 11c), tests achieved under straight oil shows reduced broaching forces and improved surface roughness.

Even the modification of the straight oil composition is essential to consider, as a variation up to 100% in roughness values was observed between the worst and the better oils tested in this study (Fig. 12).

Finally, the workpiece material composition that is the most complex and expensive parameter to modify influences the broaching forces as well as the surface quality. In this research work, the apparition of dimples has been observed while broaching only ferritic–martensitic stainless steel (X12Cr13), while pure ferritic (X6Cr17) and pure martensitic (15-5 PH) stainless steels shows no such dimples formation. This can be attributed to the alternation of phases with different mechanical properties, as well as tribo-chemical phenomenon on the tool–workpiece interface.

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Conclusion

An experimental setup has been designed in order to improve the understanding of surface roughness in broaching.

Several parameters have been investigated within a wide range of variation. It appears that surface roughness is very dependent to cutting speed and RPT values. The worst mean roughness values are obtained for high RPT and low cutting speed. The increase of cutting speed always improves the surface roughness, even under dry cutting conditions; *Ra* values obtained at 50 m/min are always around 0.15 μm. Lowering RPT is also favorable as it significantly decreases the roughness. It is however less efficient than the increase of cutting speed, mean roughness values vary from 0.1 μm in the better conditions to 2.1 μm in dry tests with low cutting speed.

Increasing rake angle also affects positively the mean roughness measured on the broached surface, as the chip evacuation is facilitated. In the worst cutting conditions, *Ra* can be varied from 2.91 μm with low rake angle tool of 15° to 0.62 μm with 25° rake angle tool. Decreasing the clearance angle under low cutting speeds also improves the mean roughness up to 46% thanks to a burnishing effect.

The cutting tool substrate appeared to have no significant effects on surface roughness, even if the cutting pressures can be reduced by the use of carbide instead of HSS.

The lubrication method directly affects the roughness of the broached surface. Reducing the friction coefficient tends to improve the surface roughness as the best results were observed under straight oil (1.27 μm for the worst cutting conditions), and the worst ones in dry conditions (near 4 μm in the same conditions). The composition of the oil used as lubricant also influences significantly the results, as a difference of 100% was observed between the more and the less effective oils.

Finally, the use of ferritic–martensitic steels has shown the apparition of dimples on the surface, whereas this phenomenon is not observed for both pure ferritic and pure martensitic stainless steel. The apparition of those dimples tends to generate a surface roughness three times higher than the ones observed without dimples.

In this work, the effects of chip curl-up on the uncut surface were also highlighted. The tool–chip contact length is as small as the chip is tightly curled-up, resulting in a reduced cutting force. Moreover the contact of the chip on the uncut surface is generating a torque on the chip root, allowing the specific forces and so cutting forces to decrease. A tightly curl-up eases the chip formation, and can consequently reduce the broaching forces.

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