Links Between Machining Parameters and Surface Integrity in Drilling Ni-Superalloy

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Keywords: Udimet 720, Drilling, Surface Integrity, Process Monitoring,

Abstract. In aerospace industry, the manufacturing of critical parts (high energy components) requires an important validation process to guarantee the quality of the produced parts, and thus their fatigue lifecycle. Globally, this validation consists in freezing the cutting conditions using metallurgical analysis or fatigue trials, and a test on the first article. This process is extremely complex and expensive. In this way establishing the correlation between the cutting conditions and the surface integrity will help us to optimize the manufacture of those parts.
In this article, by the means of an experimental method, we define a domain of validation by combining the cutting conditions according to the classic criteria established by AFNOR E66-520 norm (Couple-Tool-Material) and the criteria of surface integrity for the drilling of a Nickel-base superalloy.
The experimental device consists in drilling a Ø15.5 mm hole on a 3-axis milling centre instrumented by a 4 components Kistler dynamometer (Fx, Fy, Fz and Mz), a spindle power sensor "Watt-pilote" and three accelerometers placed following the directions X, Y and Z. Scanning Electron Microscopy (SEM) observations, micro-hardness tests and topographic measurements with an optical profilometer, are carried out to characterize the metallurgical state of the holes manufactured.
Finally, correlations were respectively made between the cutting conditions, the recorded signals and the metallurgical state of the holes.

Introduction

Gas turbine components such as discs are subjected to severe operating conditions. The manufacturing of these discs is very difficult and is submitted to important validation processes. The machining of Nickel–base superalloy is complex and some small variations of the cutting context may generate surface integrity anomalies. These anomalies, if they occur in critical parts, may have catastrophic consequences. Validation processes, during which machining conditions are "frozen" after a metallurgical analysis, are today the only way to guarantee the "health" of the produced parts. In this context, ACCENT project (Adaptive Control of Manufacturing Processes for a New Generation of Jet Engine Components) will allow the European Aero Engine manufacturers to improve their competitiveness by applying adaptive control techniques to the manufacturing of their components.
The aim of this work is to establish links between cutting conditions and surface integrity. The use of the first step of the COM (Couple-Tool-Material) methodology allows to identify optimal cutting conditions according to specific cutting forces, tool wear and roughness. We multiply ways to measure specific cutting forces in order to characterize the sensibility and the quality of those different systems. Then we try to correlate the cutting conditions with the surface integrity defined by European Aero Engine manufacturers ACCENT partners. Finally, we make some correlations between surface integrity and process monitoring signals.

State of the art

Nickel base superalloys such as UDIMET 720 are frequently chosen for turbine disc applications. In general, these alloys have good resistance against combinations of fatigue, creep, oxidation and corrosion damages. The composition of UDIMET 720 Li is given in Table 1. It is constituted by an austenitic FCC (faced centered cubic) γ matrix strengthened mainly by coherent Nickel-rich (TiAlN) γ' precipitates, and some elements such as cobalt, chrome, molybdenum and tungsten. Primary coarse precipitates γ' are clearly visible at the grain boundaries and fine cuboidal γ' are embedded coherently throughout the γ matrix [1].

Elements	Ni	Cr	Co	Ti	Mo	Al	W	Fe	B	Si	Mn	Cu	C	P	S
min	Base	17.5	14	4.75	2.75	2.25	1		0.015						
max		18.5	15.5	5.25	3.25	2.75	1.5	0.5	0.040	0.2	0.1	0.1	0.05	0.15	0.01

Table 1: Composition of UDIMET 720 LI [weight %]

Many studies on the difficulty in machining nickel-base superalloy were performed but few on drilling and even less on drilling Udimet 720 [2, 3, 4, 5]. Furthermore, the majority of papers deal with tool wear and productivity in machining Nickel-base superalloy. In hole making, the tool life may be well controlled by measuring tool flank wear but this doesn't guarantee the surface integrity [2]. The low thermal conductivity of this material leads to high cutting temperatures at the rake face which accelerates tool flank wear. The tendency of the γ matrix to work hardening and the rapid flank wear lead to a built-up edge formation. Built-up edge has consequences on surface roughness [4, 5]. In aero engine component manufacturing, a finishing operation like reaming or milling is necessary to eliminate residual stresses and work hardening generated by the roughing, and to improve the roughness specifications [2, 3, 4].
One of the most difficult steps, in aerospace industry machining, is the respect of the surface integrity and the understanding of the importance of each anomaly for part fatigue life. An important study on this topic was the MANHIRP project [7] in which they demonstrated a reduction of 1E+01 to 1E+02 cycles on fatigue life for samples (Inconel 718 and Ti64) having the following anomalies: smearing, local microstructure deformation, adiabatic shear band or heavy distortion. Other studies have demonstrated the influence of white layer or residual stresses on fatigue life [2, 3, 6, 8]. Perrin [2] has defined four types of "anomaly holes" out of the domain defined by the COM methodology [9]. The four typical holes are described by the combination of the three following anomalies: isolated smearing, shear adiabatic band, and thermo-mechanical affected zone. Out of the four typical holes, the one with exclusively "non embedded isolated smearing" doesn't impact the part fatigue life cycle. This underlines the difficulty of defining and detecting surface integrity anomalies.
Currently in aeronautical industry, an effort is conducted towards the process monitoring as a way to control the machining. Many systems exist and are efficient to control the tool wear but are not designed to control the quality of the part produced. However, some experimentation gives interesting results in feed force, acoustic emissions or spindle power. For example, feed force in drilling can enhance a burr height change, the three phases of the drilling operation, the tool wear or the tool shipping [2, 7]. In the same way acoustic emissions may enhance an abnormal drilling [7].

Experimental set up

The parts on which we carried out trials were ∅80 mm forged bars, usually used for turbine discs manufacturing. These bars have the same heat treatments as the discs (solution and aged) to obtain the nearest characteristics to the discs ones (same microstructure, same grain size ≥ 8 ASTM, and same hardness ≥ 410 HV30). The only difference between the discs and the bars is the grain flow due to the last forging operation.

The tool is a ∅15.5 mm drill Iscar Chamdrill with an interchangeable TiAlN coated carbide head. This drill has the particularity of having a very short margin (4 mm), which avoids anomalies generated by frictions all along the hole.
All the trials were made on an Olympic VK1055 3-axis vertical milling center using a 15kW spindle motor and a Fanuc Oi-MB numerical controller.
The machine was instrumented by a 4 components Kistler dynamometer (Fx, Fy, Fz and Mz), a spindle power sensor “Watt-pilote” and three accelerometers placed following the directions X, Y and Z.
Finally, we designed an assembly to manage the drilling of 6 holes per bar and to always make those holes at the center of the dynamometer. In this type of dynamometer, the torque is measured by a sensor and not calculated as in a 3 components dynamometer (figure 1a).

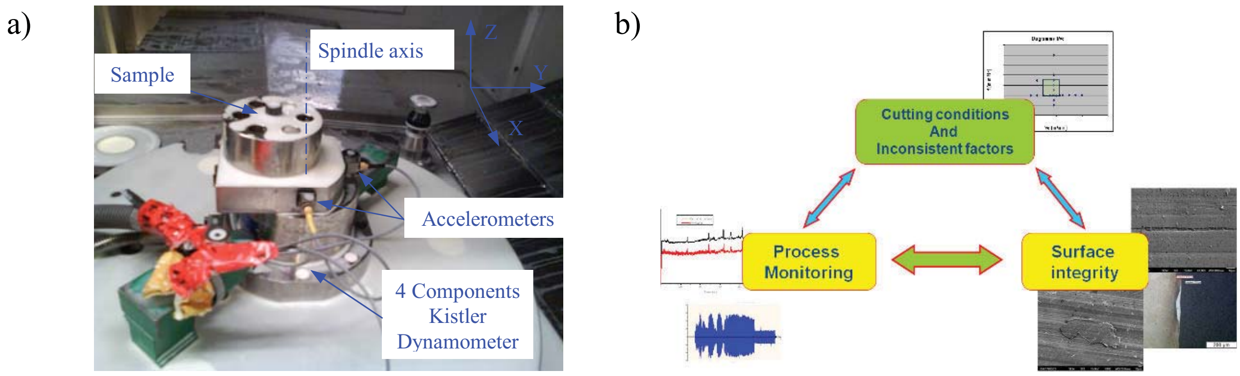

Figure 1: a) Experimental set up, and b) Experimental plan

Experimental plan

The objective of this work is to establish the relations through the cutting conditions between process monitoring signals and surface integrity anomalies (figure 1b). For our experimental procedure, we chose the first part of COM methodology to define a first domain of cutting conditions. We didn’t perform the tool life study as explained in the second part of the norm.
The operation is a ∅15.5 mm drilling in a pre-hole ∅13 mm made by electrical discharge machining. This operation is representative to the machining process of a critical part (disc) where the pre-hole ∅13 mm is a coring to make metallurgical analysis on part material.
Tests in cross as defined in the COM methodology consists, with the help of force or power sensor, in researching the cutting speed and the feed corresponding to lower specific cutting coefficients (Kc). As defined in the norm, we began the trials with the research of the reference cutting speed with fixed feed. The first feed chosen was the one used in production. Then, with this reference cutting speed we searched the reference feed. The tested cutting speeds are represented on figure 4.
Specific cutting coefficients are calculated by using equations (1) extracted from the E66-520-8 norm [2], which was defined for drilling in solid. In our case, we were close to a turning operation with a radial engagement of 1.25 mm. However, these equations revealed a good behavior and allowed quickly to reveal a cutting domain. We tested twelve different cutting speeds and eight different feeds. We machined each hole with a new tool, to minimize the influence of the cutting edge preparation and to have a good reproducibility.

$$k_{c,f}(Fz) = \frac{2 \times F_f}{d \times f} \qquad k_{c,c}(M_c) = \frac{8000 \times M_c}{d^2 \times f} \qquad k_{c,c}(P_c) = \frac{240 \times P_c}{d \times V_c \times f} \qquad (1)$$

Results

Identification of optimal cutting conditions. The cutting conditions window (figure 4) was established according to specific cutting forces Kc,f (Fz), Kc,c (Mz), Kc,c (Pc) (1) and in regards to the different measurement systems employed (figure 2). To establish the optimal cutting speed, we searched the lower point of the curve for the cutting speed graph (figure 2a) and the inflexion point of the curve for the feed (figure 2b). On figures 2a and 2b, we found an optimal point as Vc = 19 m/min and f = 0.1 mm/tr. This optimal point corresponded to the lower force necessary to cut 1 mm^2 of material.

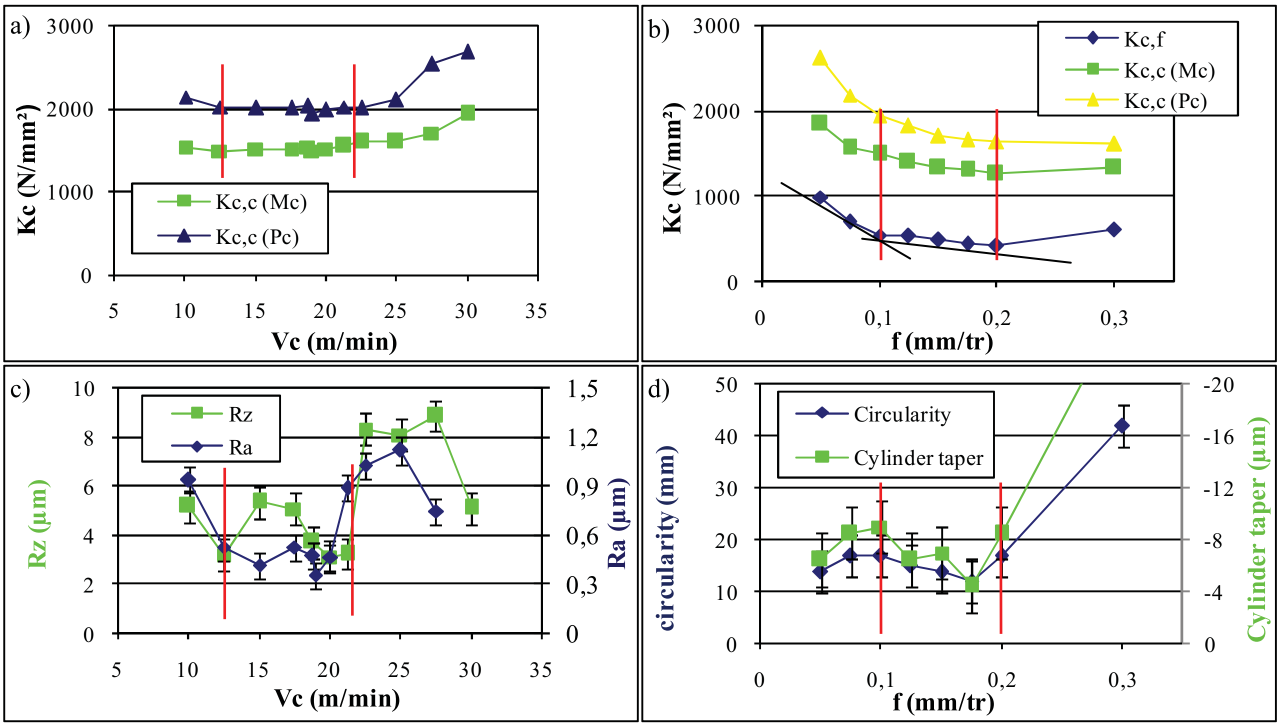

Figure 2: a) Specific cutting forces / cutting speed, b) Specific cutting forces / feed, c) Roughness / cutting speed, d) Hole geometry / feed

In our case, the definition of that point is not easy due to the incertitude of the value taken into account for the Kc calculus. Thus we have decided to establish a cutting conditions window. We delimited ranges of speed (red lines on figures 2) according to the following parameters: Specific cutting coefficients (Kc,c, Kc,f), flank and clearance wear of the tool, and roughness (figure 2c: Ra, Rz), and hole geometry (figure 2d: circularity an cylinder taper). These last two parameters are not usually used in the COM methodology. We chose them as they are non-destructive and easy to control.

Surface integrity analysis. Metallographic examinations were made in order to define cutting speed domain according to the surface integrity definition. Observations were performed with a scanning electron microscope (SEM-FEG JEOL 7000 F) and an optical profilometer VEECO (NT1100).
The surface integrity definition as shown in table 2 is a classification of anomalies in three main topics and six categories. Examples of anomalies and criteria to characterize anomalies are given.
In this paper, we focus on two surface integrity topics; the surface topography and the microstructure metallurgical changes. In the holes studied, the main anomalies observed are: chatters, smearing, micro-cracks (10-20 µm length) (figure 3), distorted layers and heat and mechanical affected layers (figure 6).

Topics	Surface topography		Microstructure Metallurgical changes			Mechanical properties	
Categories	Surface Macro anomalies	Surface Micro anomalies	Heat affected zone	Mechanical affected zone	Heat and mechanical affected zone	Material hardness changes	Residual stresses
Surface integrity anomalies	Scores, Cracks, Inclusions Orange peel, Chatter, Burr	Flaking, Smearing (chips), Laps, Plucking	Recast layer, Redissolution of phases	Distorted layer	White layer, Recrystallised zone	Deviation of Micro-hardness in surface or in depth	Deviation of residual stresses in surface or in depth

Table 2: Surface integrity definition

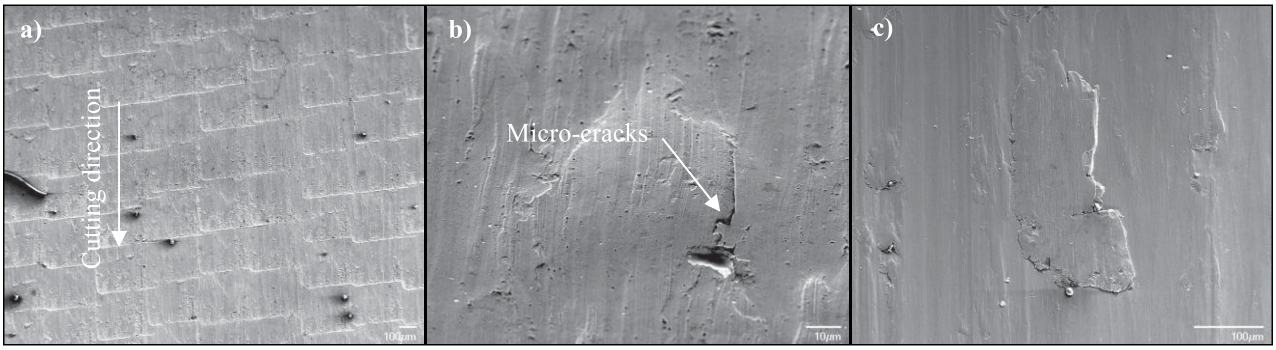

Figure 3: Surface topography anomalies: a) chatter, b) micro-cracks, c) smearing.

On figure 6b, we observe a distortion of primary γ‘ and a dissolution of primary and secondary γ‘ phases which indicates a local overheating and mechanical stresses. This analysis was correlated with an X-ray map performed with Energy Dispersive Spectrometry (SDD BRUCKER) and by micro-hardness profile where we observe the strain hardening in sub surface. More analysis with residual stresses measurements will complete those observations.

The analysis of the holes and the comparison with the specific cutting forces had permitted to determine some acceptable values for the anomalies observed. Chatters, with grooves under predetermined roughness values (Ra = 0.8 µm and Rz = 6 µm), are acceptable. Micro-cracks visible at SEM magnitude X1000 are not acceptable. Distorted layer is acceptable under 1µm thickness. And, heat and mechanical affected layer (or white layer) is totally prohibited.

Surface integrity analysis permitted to determine a new cutting speed domain, smaller than the previous one defined with COM methodology (figure 4).

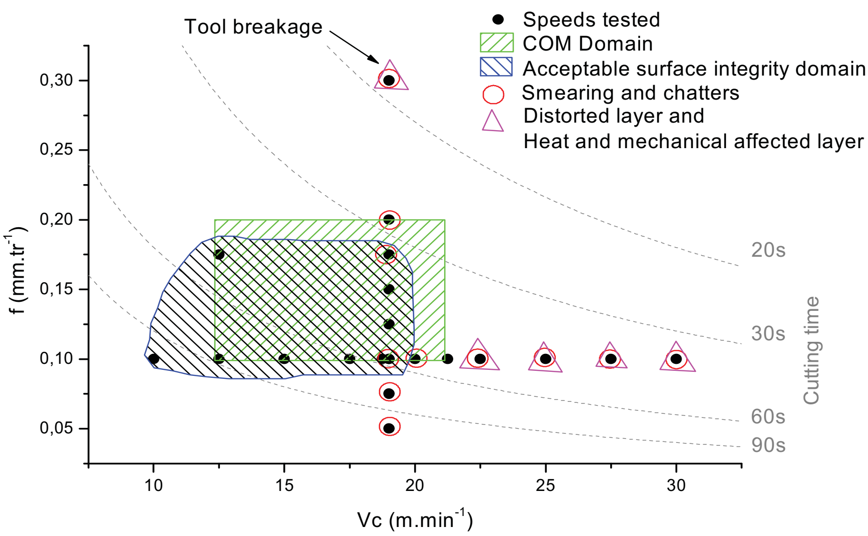

Figure 4: Cutting speeds and surface integrity domains

Signals filtrations and confrontations. Signals from process monitoring are characterized by the quantity measured, the sensibility and the filtering (sampling). The confrontation of three different systems such as power, forces and acceleration, defines their relevance towards the surface integrity. With a low pass filtering and with a cutoff frequency equal to tooth frequency, we correlated the power consumed by the spindle and the cutting power calculated (equation 2) with the torque and the feed force measured by the dynamometer. In the same way, with a high pass filter with the same cutoff frequency we can correlate signals from accelerometers and dynamometer. However, these correlations are only temporal and will be completed by a frequency analysis.
The cutting power curve given by the spindle power sensor “Watt-pilote”, is always above the cutting power curve calculated by the dynamometer. A coefficient (1.2 to 1.4 for our range of power) needs to be added in order to superpose the curves exactly. This difference is due to the “Watt-pilote” unloaded power correction and depends on the global power consumed. Actually, the amount of power consumed specifically by the spindle motor is not the same when it is unloaded as when it is in charge. This shows that the power sensor is not available for absolute measurement.

$$P = Mz \times \omega + Fz \times Vf \tag{2}$$

Correlation surface integrity – Process Monitoring. In this paragraph, we propose some correlations between surface integrity anomalies and signals recorded. The first one was the detection of some brutal changes of cutting power with some deeper cutting scores.

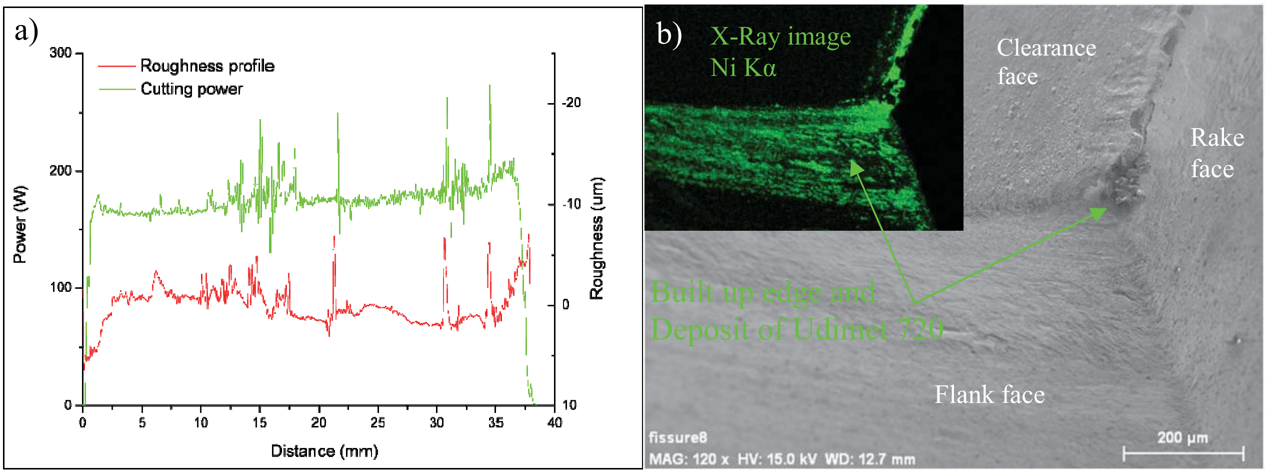

Figure 5: a) Correlation roughness/Power, b) Deposit of Udimet 720 on cutting edge of the tool

On figure 5a, we can see exactly the same pattern for the position of the peaks on both curves. The roughness profile was measured with an optical profilometer on a wide band (1 mm) all along the hole. This curve is switched upside down, in order to tally the increase in power with the increase of the removed material. The amplitude of signals variations seems proportional and further analysis will be made to confirm this. Those roughness variations could be due to the successive formation and destruction of a built-up edge which is characteristic of the Nickel-base superalloy machining [6]. Furthermore, on the figure 5b, we can see a deposit of Udimet 720 on the cutting edge tool, confirmed by Energy Dispersive Spectrometry (SDD BRUCKER) analysis. Thus, cutting power is a good way to detect some abnormal cutting condition such as built-up edge which causes abnormal cutting scores.
Figure 6 presents another example of comparison between two sensor signals and two microstructure anomalies. Along the hole we observe two similarities. The first one is a correlation between the thickness of a distorted layer and the appearance of a rapid variation of cutting power extracted from dynamometer (this observation can also be made with the torque signal). The second

one is the thickness of a heat affected layer at the same time as the cutting power increases (measured by both systems). Figures 6a and 6b show the difference in microstructure at 3 and 31mm from the hole entrance. In figure 6a, we observe a very thin distorted layer, contrary to figure 6b where we notice an important white layer and as well as a distorted layer. A micro-hardness (figure 6c) map has been drawn to show the influence of the mechanical effect in the depth of the material. This correlation between power signal and microstructure metallurgical changes was also found in three other holes (high cutting speeds on figure 4) but we could not determine exactly the cause of the sudden power change.

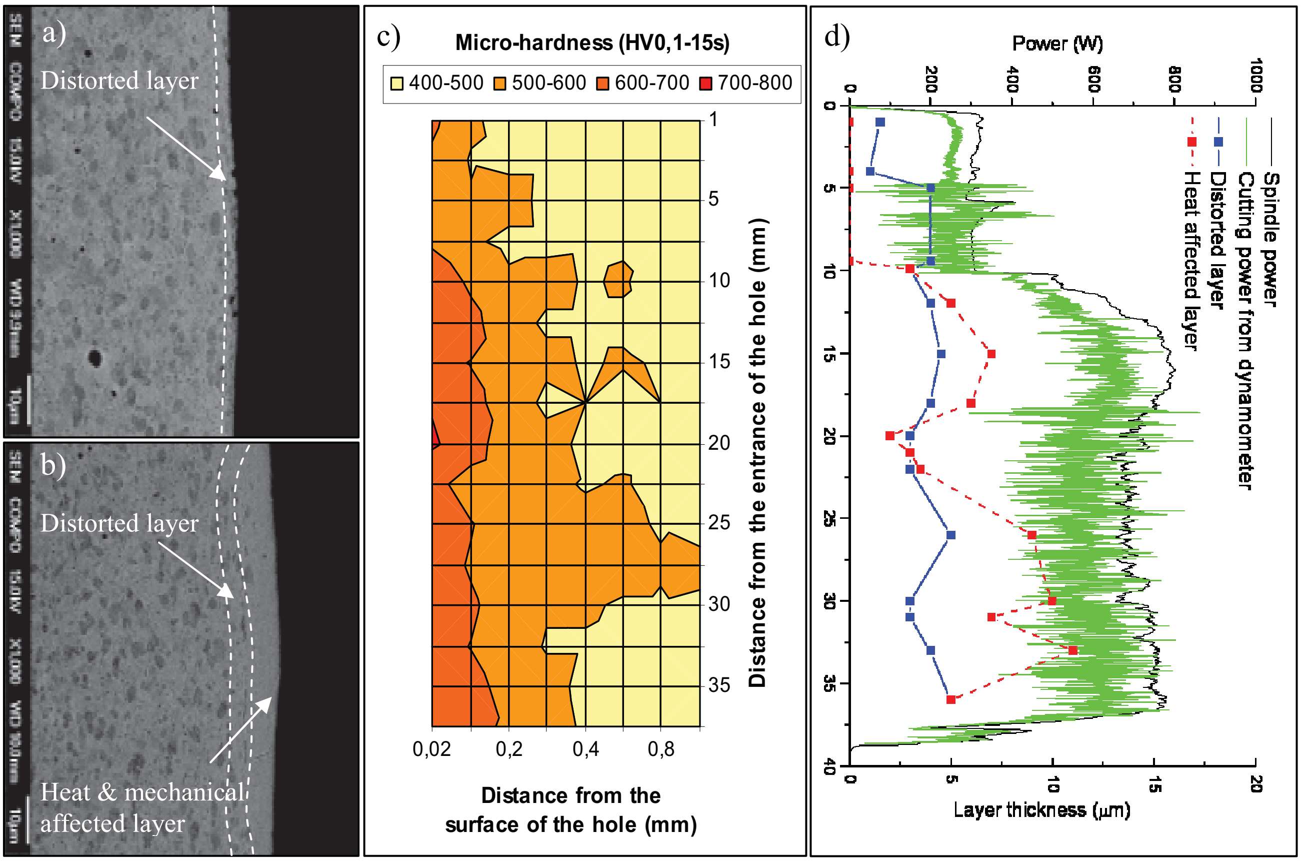

Figure 6: Microstructure at a) 3 mm and b) 31 mm from the input of the hole, c) Micro-hardness map along the hole, and d) Power signals comparison with thickness of affected layers

Discussion surface integrity – specific cutting coefficients. Metallurgical observations define a new cutting speed domain (figure 4) respecting the surface integrity definition. The optimal point defined in paragraph 4.1 is at the limit of this new domain. This result, corroborates another study [1], where it has been proved that specific cutting coefficients are able to choose an optimal operating point respecting the surface integrity definition. On the other hand, the damage free domain is smaller than the one defined by COM methodology (figure 4). The COM domain was well defined to avoid metallurgical microstructure changes but not for smearing and chatters. It indicates that parameters (tool wear, roughness and hole geometry) chosen in addition to the specific cutting forces to establish Vc/f window are not able to determine the damage free domain. This enhances that a global value such as torque or power taken into account for Kc calculus cannot detect local anomalies such as smearing or chattering. Specific cutting forces do not take into account the topology of power or forces curves.

Conclusion

In this article, we have presented the results from an experimental procedure based on COM methodology. Trials were monitored with a four components dynamometer, a spindle power sensor

and three accelerometers. Metallurgical analyses have been performed on holes produced, in order to identify and quantify surface integrity anomalies. We have compared the cutting speed domain defined with specific cutting forces, tool wear, roughness and hole geometry, with a cutting speed domain defined respecting the surface integrity definition.
Those experimentations have permitted to understand the links between specific cutting forces and surface integrity and have enhanced the lacks of the COM methodology towards local defects prevention. These have also permitted to establish correlations between surface integrity anomalies observed on the holes produced and process monitoring signals recorded during the trials. The roughness and the microstructure metallurgical changes were correlated to the cutting power signals.
In the manufacturing of aeronautic critical parts, the research or the optimization of cutting conditions are always subjected to metallurgical analyses. In this way the process monitoring may be a solution to control the surface integrity and thus, simplify the validation process as well as guarantee the absence of any other manufacturing disturbances. This particular point represents the future development of our research.

Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement number 213855.

References

[1] H.T. Pang, P.A.S. Reed. Microstructure effects on high temperature fatigue crack initiation and short crack growth in turbine disc nickel-base superalloy Udimet 720Li. Journal of Materials Science and Engineering, A 448, 67–79 (2006).

[2] G. Perrin. Étude métallurgique, mécanique et thermique de l'intégrité de surface des pièces percées au foret hélicoïdal dans l'Inconel 718TR - Détection et quantification des anomalies par Process Monitoring. Thèse de doctorat, Ecole des Mines de Paris (2004).

[3] A. Sharman, A. Amarasinghe, and K. Ridgway. Tool life and surface integrity aspects when drilling and hole making in Inconel 718. Journal of Materials Processing Technology , 200, 424-432 (2008).

[4] J. Kwong, D. Axinte, and P. Withers, The sensitivity of Ni-based superalloy to hole making operations: Influence of process parameters on subsurface damage and residual stress. Journal of Materials Processing Technology, In Press, Corrected Proof, (2008).

[5] E.O. Ezugwu. Key improvements in the machining of difficult-to-cut aerospace superalloys. International Journal of Tools & Manufacture 45, 1353-1367 (2005).

[6] A. Sharman, J. Hughes, and K. Ridgway. An analysis of the residual stresses generated in Inconel 718(TM) when turning. Journal of Materials Processing Technology , 173, 359-367 (2006).

[7] MANHIRP Project. Integrating Process Controls with Manufacturing to Produce High Integrity Rotating Parts for Modern Gas Turbines. Final Report (2005).

[8] D. Novovic, R. C. Dewes, D. K. Aspinwall, W. Voice, and P. Bowen. The effect of machined topography and integrity on fatigue life. International Journal of Machine Tools and Manufacture, 44, 125-134 (2004).

[9] AFNOR Norm NF E66-520 . Working zones of cutting tools - Couple tool-material (2000).

Advances in Structural Analysis of Advanced Materials
10.4028/www.scientific.net/AMR.112

Links Between Machining Parameters and Surface Integrity in Drilling Ni-Superalloy
10.4028/www.scientific.net/AMR.112.171

DOI References
[3] A. Sharman, A. Amarasinghe, and K. Ridgway. Tool life and surface integrity aspects when drilling and hole making in Inconel 718. Journal of Materials Processing Technology , 200, 424-432 (2008).
doi:10.1016/j.jmatprotec.2007.08.080

[5] E.O. Ezugwu. Key improvements in the machining of difficult-to-cut aerospace superalloys. nternational Journal of Tools & Manufacture 45, 1353-1367 (2005).
doi:10.1016/j.ijmachtools.2005.02.003

[6] A. Sharman, J. Hughes, and K. Ridgway. An analysis of the residual stresses generated in Inconel 718(TM) when turning. Journal of Materials Processing Technology , 173, 359-367 (2006).
doi:10.1016/j.jmatprotec.2005.12.007

[8] D. Novovic, R. C. Dewes, D. K. Aspinwall, W. Voice, and P. Bowen. The effect of machined topography and integrity on fatigue life. International Journal of Machine Tools and Manufacture, 44, 125-134 (2004).
doi:10.1016/j.ijmachtools.2003.10.018