

IDENTIFICATION OF INFLUENT FACTORS ON SURFACE INTEGRITY IN NICKEL-BASE SUPERALLOY DRILLING

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Abstract: For the critical rotating components in aeronautical industry, the metallurgical quality achieved after machining conditions could determine their mechanical behavior in fatigue. To guarantee this quality, the tools, materials and cutting conditions are frozen during the validation process by a cut-up part following by an acceptable surface integrity. Even with the fixed parameters, perturbations can occur during the process and may have a direct impact over the metallurgical quality through the apparition of anomalies, which could reduce the calculated fatigue life. The aim of this study is to define a Process Monitoring technique able to detect the thickness affected by the machining taking into account the flank wear effect. With the Pearson's correlation the most influent factors are identified and after that a linear regression is used in order to define the model.

Key words: machining of Nickel base alloy, process monitoring, Pearson, statistical methods.

1. INTRODUCTION

Table 1

The increase of turbine aero engines performances requires materials with remarkable mechanical strength at high temperature, such as UDIMET® 720 or INCONEL718. UDIMET® 720 shows important advantages, in terms of corrosion resistance (Cr), mechanical properties and oxidation behaviour (Ti, Al and Co to stabilize γ phase). The material properties and the machining characteristics lead Ezugwu [10] to classify this material as "difficult-to-machine". 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 [8].

Respecting the surface integrity is one of the most important requirements in aerospace industry. The anomalies generated by machining could have an influence on the part fatigue behaviour. Some papers deal with the influence of the "white layers" or residual stresses on fatigue life [6 and 7]. It was demonstrated that anomalies such as smearing, shear band or heavy distortion can reduce the fatigue life from 1E+01 to 1E+02 cycles [5] (Inconel 718 and TA6V samples where used).

The detection of machining process anomalies using output signals from different systems shows in the last years, one important area for the scientists and end users. The physical measures are mostly used in order to control the machining process. Spindle power changes, vibrations signature and forces can detect tool flank wear [3 and 4], the burr [1] or problems of the machine-tool (spindle bearings). Some correlations between the spin-

Variables to correlate

| Physical measures | Criteria extracted for each physical measure | Surface integrity anomalies (examples) |
|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Spindle Power (P), Torque (Mz), Forces (Fx, Fy, Fz), Accelerations (Ax, Ay, Az), Spindle Current | Mean Value, Standard Deviation [SD], RMS, Skewness, Kurtosis | Thickness of the Thermo-mechanically affected layer, smearing, burr length, micro-hardness deviation, etc |

dle power and surface roughness or metallurgical changes are treated by Dutilh [2].

The different statistical methods (Design of Experiments for example) permit to quantify the influence of the cutting parameters on surface or subsurface [9 and 11]. Once the most important parameters are identified, the linear relations between the terms could be determined with Pearson correlations and further, the linear regression can establish the relations between variables [11].

Regarding the important number of physical measurements, criteria and surface integrity anomalies, almost 100 variables to correlate (Table 1), the choice of statistical methods is justified. Automating the analyses, this model will help us to see which factors have an important contribution to generate an unacceptable surface integrity and make further Process Monitoring proposals. In the same direction, European Project ACCENT (Adaptive Control of Manufacturing Processes for a New Generation of Jet Engine Components) tries to develop new Process Monitoring systems to control the fabrication process and also to reduce the validation costs.

Through an experimental approach, the impact of machining disturbances on the surface integrity and mon-

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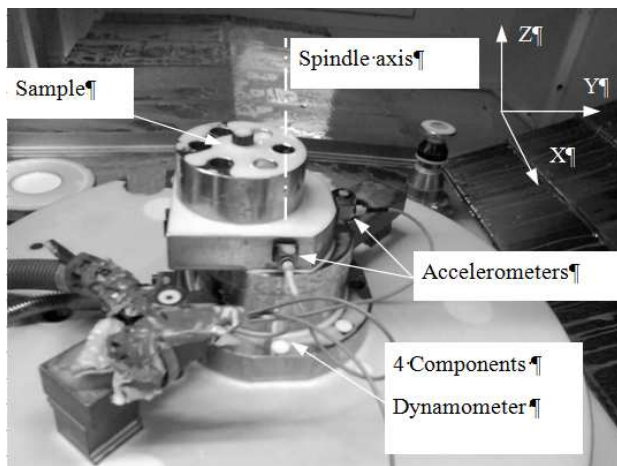


Fig. 1. Experimental set up.

itoring signals is studied. Using a statistical method, a model is proposed for monitored in “real time” of the thickness affected by the machining, taking into account the flank wear behaviour.

2. EXPERIMENTAL WORK

2.1. Work material and equipment

The parts on which we carried out trials were $\varnothing 80$ mm forged bars, usually used as raw materials before forging turbine discs. These bars have the same heat treatments as the discs (solution Heat Treatment and aged) to obtain the nearest routine mechanical properties to the original discs (same microstructure, same grain size ≥ 8 ASTM, and same hardness ≥ 410 HV30).

The tool is a $\varnothing 15.5$ 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.

The operation is a drilling in a pre-hole $\varnothing 13$ mm and the length of the hole is 37 mm.

2.2. EXPERIMENTAL SET-UP AND MEASURING INSTRUMENTS

All the trials were made on a HURON KX10 3-axis vertical milling centre using an 18kW spindle motor and a Siemens 840D numerical controller.

The machine-tool was instrumented by a 4 component Kistler dynamometer (F_x , F_y , F_z and M_z), and three accelerometers placed following the directions X, Y and Z (Fig. 1). The spindle power, the position of Z axis, the spindle current intensity and the three axes current intensity are recorded through the Siemens Profibus.

Metallographic examinations were carried out on all the experiments with an optical microscope (Olympus GX51), a scanning electron microscope (SEM-FEG JEOL 7000F) and a micro-hardness tester (SHIMADZU HMV).

2.3. Experimental procedure

The present paper is part of an important study on drilling Nickel-base superalloys which takes place in the European Project ACCENT. It presents several steps, as follows:

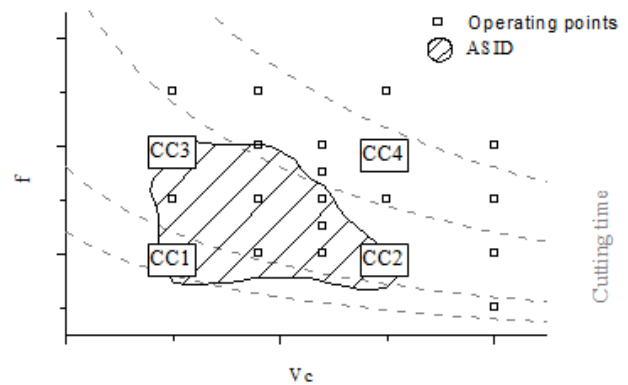


Fig. 2. Acceptable Surface Integrity Domain and operating points.

- In a first time [2], combining the cutting conditions according to the classic criteria established by the French specification AFNOR E66-520 (Couple-Tool-Material) and the criteria of surface integrity, an Acceptable Surface Integrity Domain is defined (ASID-Fig. 2). This “window” was founded exploring different values of the cutting speed and feed rate and regarding to the specific cutting forces K_c , the tool wear, roughness, hole geometry, without γ' dissolution layer and to minimize the distorted layer.
- A second experimental campaign [12] treats the impact of a cutting fluid interruption on the surface integrity and on the Process Monitoring signals.
- In this paper, a new experimental campaign is considered. Based on results of the first tests, new trials were performed in order to understand the influence of machining disturbances (hardening changes of the material, tool position defect or cutting fluid emulsion variation) on the surface integrity and physical measurements.

In order to study the influence of the cutting parameters and interactions between them on the ASID, the trials were performed according to a Fractional Experimental Design with 2 levels (1 or 2) for each one of the five factors (cutting speed, feed rate, material hardness, position defect and cutting fluid emulsion). We chose to alias a factor with the interaction of order 4 to reduce the number of trials to 16 experiences and get a $2^{(5-1)}$ resolution 5 plan. If the five parameters are noted A, B, C, D, E, the alias structure is:

$$\begin{aligned}
 &A + BCDE; B + ACDE; C + ABDE; D + ABCE; \\
 &E + ABCD; AB + CDE; AC + BDE; AD + BCE; \\
 &AE + BCD; BC + ADE; BD + ACE; BE + ACD; \\
 &CD + ABE; CE + ABD; DE + ABC.
 \end{aligned}$$

The hardness H1 is 6% under the hardness H2. This variation was generated by changing the aging treatment but the microstructure is similar (grain size and γ' phase proportion).

The tool position defect was generated with an x axis displacement compared to the pre-hole. The value was fixed at 0.05 mm which corresponds to twice the value of the production limit.

The emulsion variation was established as the limit acceptable in production. The maximum percentage was fixed according to the example of the industrial situation.

Table 2

Experimental Design

| No | Cut-ting speed | Feed rate | Material hardness | Position over the hole before [mm] | Cut-ting fluid emul-sion % |
|----|----------------|-----------|-------------------|------------------------------------|----------------------------|
| 1 | Vc1 | f1 | H1 | 0.05 | 7.5 |
| 2 | Vc1 | f1 | H2 | 0 | 7.5 |
| 3 | Vc1 | f2 | H1 | 0 | 7.5 |
| 4 | Vc1 | f2 | H2 | 0.05 | 7.5 |
| 5 | Vc2 | f1 | H1 | 0 | 7.5 |
| 6 | Vc2 | f1 | H2 | 0.05 | 7.5 |
| 7 | Vc2 | f2 | H1 | 0.05 | 7.5 |
| 8 | Vc2 | f2 | H2 | 0 | 7.5 |
| 9 | Vc1 | f1 | H1 | 0 | 12.5 |
| 10 | Vc1 | f1 | H2 | 0.05 | 12.5 |
| 11 | Vc1 | f2 | H1 | 0.05 | 12.5 |
| 12 | Vc1 | f2 | H2 | 0 | 12.5 |
| 13 | Vc2 | f1 | H1 | 0.05 | 12.5 |
| 14 | Vc2 | f1 | H2 | 0 | 12.5 |
| 15 | Vc2 | f2 | H1 | 0 | 12.5 |
| 16 | Vc2 | f2 | H2 | 0.05 | 12.5 |

The cutting conditions parameters used in the industrial applications cannot be disclosed, so the confidential values are changed by indicative variables.

3. FRACTIONAL EXPERIMENTAL DESIGN RESULTS

The surface integrity of each hole was characterized by the thickness of the γ' dissolute layer (Fig. 3), the distorted layer, the presence of plucking and smearing, the burr and the micro-hardness value observed at 40 μm from the surface. For example, in

Fig. 3, a discontinuous thermo-mechanically affected layer (8 μm) is presented.

The analysis of the experience plan shows that the influencing parameters on the two types of layers and plucking are the emulsion, the hardness and cutting conditions.

The main influential factors on flank wear are the cutting speed and the interaction between the hardness and position defect (Fig. 4). The evolution of the tool flank wear is significant (even three times between tests).

The position defect does not lead to global anomalies on the entire length of the hole or premature degradation of the tool, but local defects can be observed (Fig. 5). This type of anomaly is not always visible.



Fig. 3. Example of γ' dissolute layer.

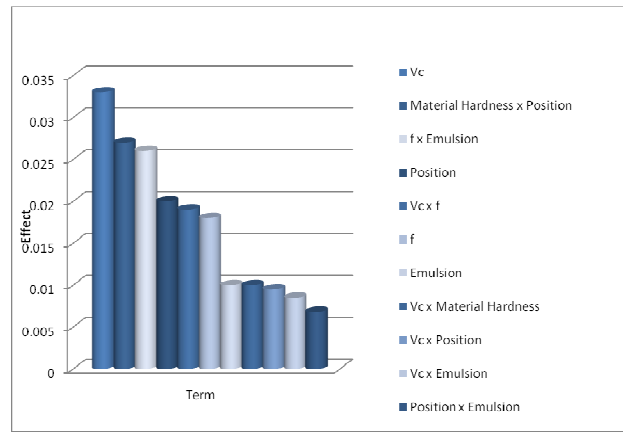


Fig. 4. Pareto Chart for the main effects on tool flank wear.

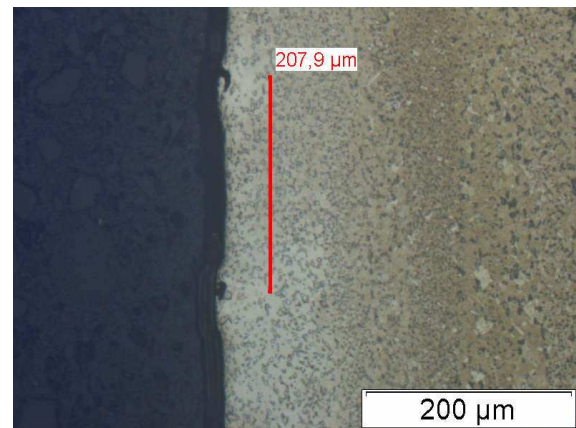


Fig. 5. Example of surface integrity anomalies due to the position defect.

The analysis of the experimental plan shows that the run out has an influence on the smearing and micro-hardness but given the random distribution of the chips and the large dispersion of micro-hardness measurements, will not be consider in this study. The apparition of the γ' dissolute layer is connected with the evolution of the emulsion and the material hardness.

The thickness of the γ' dissolute layer varies with the cutting conditions and hence the cutting forces (this observation was also made during the study of the establishment of the ASID).

Contrary to the γ' dissolute layer, the distorted layer (corresponding to a layer where the γ' phase are elongated) is correlated with a more important hardness. On the other hand they evolve in the same sense for the feed and emulsion. Those results have to be balanced with the experimental examination methodology. In the case of the distorted layer, the examination is difficult and it is submitted to the appreciation of the examiner which classify holes by grades (5, 10, 15, 20 μm distorted). Maybe this type of examination has to be completed by a more objective analysis as micro-hardness measurement.

The results obtained are very instructing and in the same time surprising (the emulsion which is the most influent factor on the thermo-mechanically affected layer) but could be due to the scattering regarding the measures or maybe to the experimental design type. Indeed the factor effects are not pure and even if the interactions orders 4 are neglected, the interactions order 3

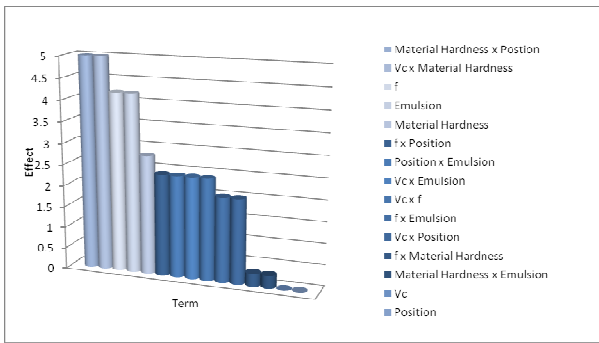


Fig. 6. Pareto chart of the effects on affected layer.

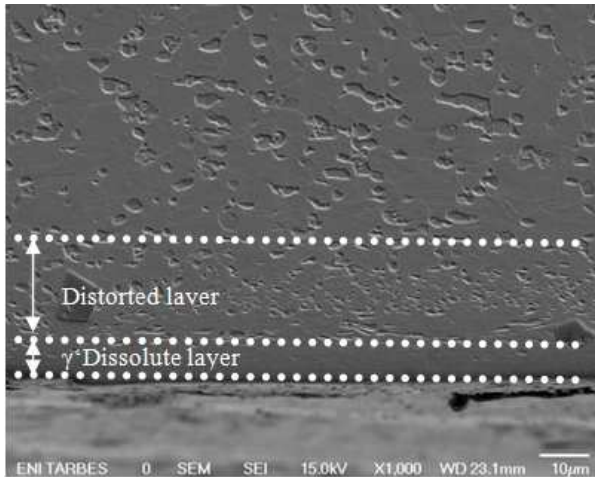


Fig. 7. Thickness of affected layer by drilling.

(summed with interactions order 2) must be included in the study. After that is difficult to determine which is the most influent between the interaction order 3 and order 2. Further analyses will be done in order to verify and understand better these relations.

Further, the sum of two types of layers (sum of the distorted layer and the γ' dissolute layer) will be considered in this study (Fig. 7) in order facilitate future analysis and to define a Process Monitoring technique able to estimate in real time the thickness affected by the drilling operation.

The first analyses of the experimental plan were made in order to understand the influence of the cutting parameters on the surface integrity. Now, the impact of the parameters on the process monitoring signals will be study.

Among all the signals and the cutting conditions parameters, the bests correlations could be made between the Position and the Mean values for F_y and F_x (visible by analyzing the experimental plan and at the same time with Pearson Correlations – Table 3). The defect has been introduced artificially on the x axis and it is easy to understand the contribution of the position following F_x . The fact to detect the defect on F_y suggests that another defect of position or run-out at least as important as the one introduced. For the same reason, the defect of position couldn't be put in evidence by frequency analysis (observation of the frequency rotation and harmonics). It shows that the position defect was not important enough in order to generate a meaningful variation of the surface integrity and on the Process Monitoring signals.

Table 3

Examples for the linear matrix

| Variables | Affected layer | Flank Wear | Margin Wear |
|--------------------|----------------|-------------|-------------|
| Cutting speed | -0.01 | 0.53 | 0.4 |
| Feedrate | 0.47 | 0.29 | 0.28 |
| Position | -0.09 | 0.31 | 0.39 |
| Emulsion | -0.51 | -0.16 | 0.28 |
| Material Hardness | 0.16 | -0.07 | 0.43 |
| Mean M_z | 0.55 | 0.66 | 0.49 |
| SD_{F_z} | 0.56 | 0.85 | 0.43 |
| SD_{F_y} | 0.57 | 0.38 | 0.23 |
| SD_{F_x} | 0.54 | 0.3 | 0.26 |
| Flank Wear | 0.62 | 1 | 0.33 |
| Margin Wear | 0.025 | 0.33 | 1 |
| Mean $I_{spindle}$ | 0.54 | 0.6 | 0.5 |
| Mean P_{power} | 0.38 | 0.76 | 0.58 |

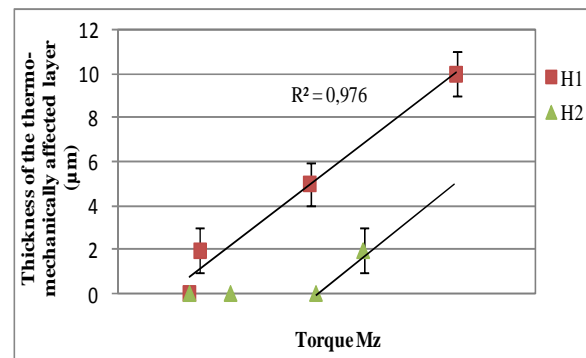


Fig. 8. Thickness evolution of γ' dissolute layer vs. torque M_z .

These experimental trials show that the ASID (Acceptable surface Integrity domain) defined for one context (one emulsion percentage, hardness), may not be exactly the same for another context. If we consider only the tests for a 7.5% emulsion and that one compares with results achieved for the second hardness could be observed a relation between the M_z couple and the thickness of the thermo-mechanically affected layer (same relation already observed by Dutilh [2] and Perrin [6] – Fig. 8). Nevertheless, this relation proves to be confirmed only for pieces presenting hardness H1. The cutting conditions explored do not permit to verify if the efforts observed have the same evolution of the thickness for hardness H2. This model does not take into account the defect of position because we observed previously that this one does not have an influence on the thermo mechanically affected layer.

4. PEARSON'S CORRELATIONS

Alongside the experimental plan analyses, another statistical method was introduced in this study to quantify the different relations.

The Pearson’s correlation matrix describes the correlations among the variables described (cutting parameters, surface integrity criterion and the physical measures). It is a square symmetrical $P \times P$ matrix with the diagonal elements equal to unity (correlations of variables with themselves). The correlation coefficient (r_p) represents the linear relationship between two variables and the values are between -1 and 1 (0 – no correlation; ± 1 high correlation).

For each physical measure, different criteria were extracted (Table 1) and with the surface integrity anomalies, a first matrix was defined. In order to analyze the linear correlations between the terms of the matrix we are using a statistical approach (Pearson Correlations) and a new correlations matrix is fixed.

This method comes to confirm the results obtained by analyzing the experimental plan. For example, the fact that the position defect doesn’t have an influence on the apparition of the thermo-mechanically affected layer is shown by correlation coefficient $r_p = 0.024$. In the case of this study, when the Pearson’s Correlation is used, the intensity between two variables is not so important due exactly to the fact that this statistical method does not take into account the interactions between variables.

5. MODEL

The linear matrix gives information about the factors which have to be considered in the different models. Some high correlation coefficients can be observed in the Table 3 corresponding to affected layer column.

In order to define a model able to estimate the thickness affected by the drilling operation, it is necessarily to consider only the terms having a high correlation coefficient (M_z , SD_{Fz} , SD_{Fy} , SD_{Fx} , and Flank Wear – Table 3). Also, for this model, the most important interactions between cutting parameters (Fig. 6) Fig. 6 will be taken into account. The emulsion and the feed rate are important factors in Fig. 6 and Table 3. The $Mean_{Power}$ has an important coefficient (Table 3) but will not be considered in the study (it is already tested and is not improving the model). So, we can write the follow equation:

$$\begin{aligned} \text{Affected layer} = & \beta_1 + \beta_2 \cdot f \cdot \beta_3 \cdot \text{Emulsion} + \\ & \beta_4 \cdot \text{Mean}_{\text{Spindle}} + \beta_5 \cdot \text{Mean}_{M_z} + \beta_6 \cdot SD_{Fz} + \\ & \beta_7 \cdot SD_{Fy} + \beta_8 \cdot SD_{Fx} + \beta_9 \cdot \text{Flank Wear} + \\ & \beta_{10} \cdot V_c \cdot \text{Hardness} + \beta_{11} \cdot \text{Hardness Position} . \end{aligned} \quad (1)$$

Regarding these terms, the emulsion, hardness and tool position can be measured before the machining, the torque, the forces along the three directions can be monitored with a dynamometer. The spindle current can be monitored using the NC of the machine tool, but the flank wear could be measured only at the end of the process. To reach the goal of this model, in a first time the tool wear flank should be expressed as a function of process monitoring signals.

Coming back to the matrix correlations, we search the most influent factors on the flank wear. For this model, three factors will be taken into account considering the highest values (the standard deviation for the axial force Fz and the mean value for the power and torque), having the expression:

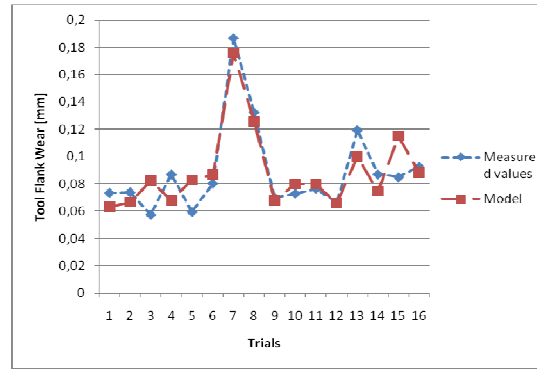


Fig. 9. Comparison between measured values for the flank wear and the model.

$$\text{Flank Wear} = \alpha_1 + \alpha_2 \cdot \text{Mean}_{M_z} + \alpha_3 \cdot SD_{Fz} + \alpha_4 \cdot \text{Mean}_{\text{Power}} . (2)$$

But, the power was obtained using the expression:

$$\text{Power} = M_z \cdot \omega \cdot 2\pi + F_z \cdot V_f .$$

The coefficients α_1 , α_2 , α_3 and α_4 are identified using a multiple regression. Replacing the coefficients with their values and the power expression, the model will be:

$$\begin{aligned} \text{Flank Wear} = & 0.02367 - \\ & \text{Mean}_{M_z} (0.0099 + 4.49 \cdot 10^{-5} \cdot 2\pi \cdot \omega) + \\ & 0.00146 \cdot SD_{Fz} - 4.49 \cdot 10^{-5} \cdot F_z \cdot V_f . \end{aligned} \quad (3)$$

The results of the flank wear model are compared with the measured values in Fig. 9.

Some remarks can be made regarding the Fig. 9:

1. The mean error between the model and the measured values is 2.7% and a standard deviation of 20%.
2. Some trials have a high error and this could be explained by the fact that the terms of the model were chosen regarding the highest linear correlation coefficients and the interactions between different cutting parameters are neglected by the statistical method. As observation, an important error is registered for the tests having H1 hardness and no position defect (exactly the interaction presented in Fig. 4).

Once the wear behaviour is known, the next step is to insert (2’) in the expression of anomaly (1). The coefficients β_1 , β_2 , β_3 , β_4 , β_5 , β_6 , β_7 , β_8 , β_9 , β_{10} and β_{11} were founded using the multiple regression.

$$\begin{aligned} \text{Affected layer} = & -70.03 - 397.31 \cdot f - 0.65 \cdot \text{Emulsion} + \\ & 4.78 \cdot \text{Mean}_{\text{Spindle}} + 40.3 \cdot \text{Mean}_{M_z} - 4.1 \cdot SD_{Fz} + \\ & 0.26 \cdot SD_{Fy} - 0.164 \cdot SD_{Fx} + 2788.79 \cdot \text{Flank Wear} + \\ & 5.9 \cdot 10^{-6} \cdot V_c \cdot \text{Hardness} - 0.366 \cdot \text{Hardness Position} . \end{aligned} \quad (4)$$

The blue line represent the values measured for the affected layer thickness. This one is compared with the model obtained-red line. The mean error is 0.24% and the standard deviation 8.3%.

In Fig. 11, it is visible the correlation coefficient ($R^2 = 0.97$) between the model and the measured values.

This model could be a first step in order to develop some Process Monitoring tehcnics able to detect anomalies in “real time”.

However, it is important to notice that this model could be used only for the cutting parameters tested in these tests. Even if the results obtained are good, maybe

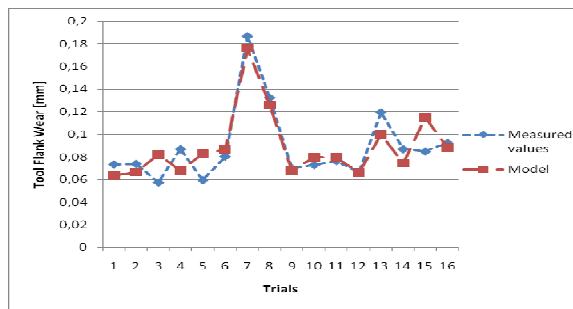


Fig. 10. Comparison of the measured values and the model for the affected layer thickness.

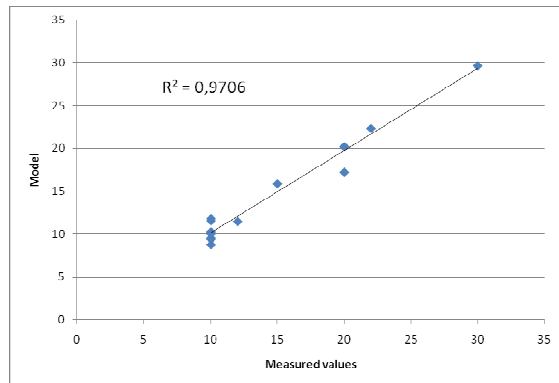


Fig. 11. Correlation between model and measured values.

the linear model is not the best the choice. Also, a simplification for the model could be one of the next steps. But, a simplified model, leads to an important error. For this reason, we have to find a way to improve the model.

For instance, only global analysis were performed. Future researches will be focused on local analysis and also the accelerometers signals will be considered.

The implementation of this process monitoring strategy in the industrial area it is difficult. The fitting of machine tools with dynamometers will generate high costs and therefore future researches will try to define new systems more simple. As example, the dynamometer's outputs (F_x , F_y , F_z and M_z) replaced with the signals from NC of the machine tool (the current for the three axes and the spindle power signal).

6. CONCLUSIONS

This paper presents the results obtained from an experimental campaign where some machining disturbances were tested (hardening changes of the material, tool position defect or cutting fluid emulsion variation). The trials were monitored with a four components dynamometer, a Siemens signals recorder and three accelerometers. Metallurgical analyses were performed on the holes produced, in order to identify and quantify surface integrity anomalies.

Using a statistical approach, a model able to detect the affected layer thickness by the drilling operation was defined. For the monitoring systems outputs and surface integrity anomalies were defined different criteria. With the Pearson's correlation, the most important factors on the affected layer were defined. One of the highest correlations corresponds to the flank wear. The tool flank

wear was expressed as a function of PM signals and then introduced in the affected layer equation. In the end, the thickness of layer affected is a function depending only on physical measurements and cutting parameters.

Moreover, the evolution of the affected layer with the torque M_z could be a way to monitor the machining. But, it has to be taken into account the influence of the material hardness regarding the effects on the apparition of anomalies.

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