On line Diagnosis Strategy of Thread Quality in tapping

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RESUMEN

El roscado es una de las operaciones más comunes en mecanizado. Consiste en esculpir los hilos de la rosca sobre la pared de un agujero previamente taladrado mediante una herramienta llamada macho de roscar. Cuando los machos son nuevos o están ligeramente desgastados, el proceso suele estar en control y la geometría de la rosca es correcta. Pero cuando el macho incrementa su desgaste, la geometría de la rosca se modifica llegando a estar fuera de tolerancias.

El objetivo de este artículo consiste en desarrollar una aplicación industrial de monitorizado (SPC) que adquiera la corriente del husillo principal y en base a esta señal asegure la calidad de la rosca. Este sistema trabaja en tiempo real e indica cuándo el desgaste del macho es crítico que, si el proceso continuara, mecanizaría roscas fuera de tolerancias. Luego el sistema enciende una luz roja que permite al operario reemplazar el macho desgastado. Dicho sistema sería económico puesto que el proceso de roscado podría ser ejecutado sin intervención de operario.

Palabras clave: roscado, monitorizado, diagnosis, calidad, PCA, SPC.

ABSTRACT

Tapping by cutting is one of the most common operations in manufacturing. It consists of cutting internal threads on the wall of a previously drilled hole by means of a tool called a tap that has cutting edges on its chamfered periphery. When taps are new or slightly worn the process is usually in control and the geometry of the resulting threads on the work piece is correct. But as the tap wear increases the thread geometry deviates progressively from the correct one and eventually the screw threads become unacceptable.

The aim of this paper consists on an industrial monitoring application (SPC) to data coming from the current signal of the tap spindle for assessing thread quality. It operates on line and indicates when the tap wear is so critical that, if the process were continued, it would result in unacceptable screw threads. Then the system shows a red light so that the operator could replace the worn-out tap. The system would be very cost-effective since the tapping process could be run without any operator intervention.

Keywords: tapping, monitoring, diagnosis, quality, PCA, SPC.

1. Introduction

Tapping by cutting is one of the most common operations in manufacturing. It consists of cutting internal threads on the wall of a previously drilled hole by means of a tool called a tap that has cutting edges on its chamfered periphery. The process is similar to broaching but the tool teeth move along a helix instead of following a straight line as in broaching. Tapping is a difficult operation due to the large number of cutting edges involved [1] and the complicated synchronization necessary between the rotational and the feed movements of the tap, a task particularly difficult at high speeds [2].
Naturally, wear deteriorates the sharpness of the cutting edges of the teeth and as a result the cutting process demands more energy and produces more heat. With increasing heat the teeth soften, wear accelerates, the tip of the teeth becomes prone to chipping, and in some cases the clearance of the faces gets progressively loaded with welded work piece material. As a result, the quality of the tapped thread flanks worsens and the major diameter of the threads diminishes producing unacceptable threads. Eventually, the tap itself can break. Among these problems, tap breakage is a serious concern because when it happens the process has to be stopped, the broken part of the tap has to be extracted from the work piece and the damage in the work piece needs to be repaired. Given that tapping is usually performed at the end of the product flow, when the work piece has reached high added value, it is of interest to predict when these problems will occur in order to avoid them. In the past, some work has been devoted to monitor tap wear in order to predict when the tap will break [3-6] and as a result there are some commercial systems available for this purpose. However, as far as we know, no work has been done on the automatic detection of the point in time when the threads will be unacceptable from the dimensional point of view and this is addressed in the present paper.

In this paper, we detail the experimental development and implementation of a new automatic monitoring and classification system aimed at predicting the point in time when the tapped threads become unacceptable as a result of tap wear. As discussed later, the system is implemented on-line, requires no intrusive sensors, and allows for automatic worn-out tap replacement. The proposed system is particularly useful in high speed tapping machines, where typically an operator attends several machines simultaneously. In this case, even with a good synchronism between rotational and feed movements, the process can not be kept in control for a long time if the worn out taps are not removed from the machine and substituted by new ones.

While there exist mechanistic models for tapping [1, 7-12], the reliability of such models is low given the inherent noise in this complex process. Instead, this paper will describe a monitoring and classification system in which certain process signals, related to the process state, are monitored.

Related previous work on tap modelling has focused on fault detection and classification for diagnosis purposes, starting from the work conducted by Chen at al. [4], based on Sha’s Ph.D. thesis [3]. Their approach considers the on-line detection of three specific types of process faults: a) wear in the tap; b) misalignment between the tap axis and the axis of the previously drilled hole; and c) under/over dimensioning of the diameter of the hole. They measured tap torque and force signals using an intrusive dynamometer, from which peak torque and thrust force parameters were selected for fault detection purposes. Their system then classifies the tapped threads according to each of the types of fault using a conditional probability approach. This work was continued by Liu et al. [5], who used a neural network to classify the faults. Both papers relied on intrusive sensors in the cutting area which reduce work volume and increase cost due to tool handling difficulties. Further work in this line was by Li et al. [6], whose system detects the same three types of faults of the previous papers but used less intrusive sensors. They replaced the dynamometer by an eddy current sensor attached to the spindle motor. The electrical current of the spindle motor was modelled using wavelets, and the wavelet coefficients most sensitive to thread quality were selected as monitoring parameters. Principal Components were employed to reduce the dimensionality of the coefficients and reduce correlation among them. The principal component coefficients were fed into a neural network for fault classification purposes. Reported results agreed reasonably well with experiments. Since the sensors utilized do not reduce work volume, this system represented a definite advancement over previous approaches to tap quality control. Still, the sensors utilized involve an additional cost, and the system requires production of unacceptable threads under each of the 3 types of process faults for training purposes.

Although Li et al. [6] used non-intrusive sensors and this reduces cost, we present a more cost effective solution in which the electrical current signal is acquired directly from the I/O module of the CNC machine itself, and hence, no sensors are required. In contrast with earlier research on tap modeling, our emphasis is on process monitoring of the tap tool and on the classification (prediction) of the corresponding thread quality, rather than on fault detection and classification of the tapping process with respect to a specific set of process conditions. The proposed system monitors the overall condition of the process with respect to tool wear, maximizing the time the tap produces acceptable threads. The monitoring system has the advantage of not requiring the production of defective threads. A two-class classification approach is also presented which indicates the thread quality can be predicted with high reliability using certain spindle motor torque parameters, which we describe in detail.
The rest of this paper is organized as follows. Section 2 shows experimental set up is described and current/torque signal is selected to diagnosis the thread quality. Section 3 describes in detail the parameters (areas under the torque signal) used and their interpretation in the physics of the process. Section 4 presents the multivariate statistical techniques applied to the torque area parameters: Principal Component Analysis (to reduce the number of parameters monitored) and a Generalized Variance control chart (to monitor the principal components of the torque signals). Finally, Section 5 describes an implementation and validation of the on-line monitoring system of thread quality in an industrial environment.

2. Experimental set up and signal selection

Tapping operations are performed on two different CNC machining centres (Groupe Tivoly and Fagor Ederlan factory) using four flutes metric M10x1.25mm High Speed Steel (HSSSE) taps Titanium Carbonitride (TiCN) coated.

Experiments in Groupe Tivoly

Work piece material is cast iron (GG25) in 250 by 550mm plates 20 mm thick. A speed of 20m/min and no coolant are selected. The tap holder allows 12mm axial extension, 0.8mm axial compression and 0.1mm radial displacements to compensate possible synchronism errors that may occur during tapping. One thread is tapped in the spindle motor of Groupe Tivoly configuration.

Experiments in Fagor Ederlan factory

Work piece material is cast iron (GG25) in a brake wheel (Figure 1). A speed of 15m/min and Minimum Quantity Lubricant (MQL) are selected. The tap holder allows 4mm axial extension and nothing axial compression to compensate possible synchronism errors that may occur during tapping. The Figure 1 shows the set up in a manufacturing cell and the brake wheel which is tapped.

Four threads are tapped simultaneously in the spindle motor of Fagor Ederlan configuration. This is a trouble because the current/torque signal is the sum of four taps. However, the goal of this paper is to obtain a monitoring system which detects the lack of thread quality independent of the machine tool configuration.

![Spindle motor and brake wheel setup](image)

Figure 1. Set up in the manufacturing cell and a brake wheel from Fagor Ederlan factory.
In both configurations, to assess thread quality, all tapped threads are inspected by a “go-no-go” gauge. Preliminary results show that the losing of thread quality always happens some time before the tap is really worn out, therefore it will be assumed that the tap end of life is reached when the tap still produces unacceptable threads either because: a) the “no-go” gauge goes for more than two and a half threads (oversized threads), or b) the “go” gauge does not go (undersized or deformed threads, as a consequence of a reduction of the tapped threads height as a result of tap main edges wear and subsequent retraction). In this paper preliminary experimental work has shown that quality loss has always been due to undersized and oversized threads.

And as torque can be easily calculated by measuring the spindle motor current it has been decided to select the motor current as the monitoring variable for thread quality.

Consequently during tapping of each hole the spindle drive current/torque signal is captured, sampled at 1000Hz, through data acquisition board and stored in a PC for analysis.

3. Parameters from spindle motor torque signal

The evolution of the current/torque signal during the execution a cycle (1st hole of tap 1) can be observed in Figure 2 where seven areas are identified by an A letter followed by subscript. Those areas have been selected as potential parameters for diagnosis will now be described and their sensitivity assessed.

![Torque signal; Tap 1 & Thread 1st](image)

*Figure 2. Torque signal from the spindle drive during tapping operation.*

Area A₂ represents the cutting torque area during the tapping operation (cutting stage) itself when the chamfer teeth (Figure 2) engrave the thread profile progressively onto the wall of the previously drilled hole. Area A₃ corresponds to the deceleration torque required for stopping the main spindle. Area A₄ represents the tap torque while the tap conducts minute angular moves to keep the spindle angular speed equal to zero while the tap is at the bottom. A₅ and A₆ correspond to the tap torque required for accelerating the spindle from zero to the cutting speed in the reference plane and at bottom, respectively. Area A₇ represents the torque time evolution induced by the friction of the active cylinder teeth when sliding on the newly tapped threads during the tap reverse stage. A₈ and A₉ correspond to the tap torque required for decelerating the spindle from cutting speed to zero at bottom and in the reference plane, respectively.

One of the approaches could be to find the group of the A parameters with the great discriminator power with respect to wear/thread quality. But this task is complicated and to make it simpler it is let us...
first get the parameter number reduced. For this task the Principal Component Analysis (PCA) will be applied. Then Statistical Process Control is described to obtain a statistic to diagnosis the thread quality.

4. PCA to reduce the parameters & SPC to diagnosis.

PCA is a statistical technique that groups a set of parameters or original variables in a set of lineal and uncorrelated functions called Principal Components or PCs. But although the number of PCs is equal to original variables, it is easy, however, to find that only a few of them (2 or 3) can give a high enough percent (80-95%) of the evolution of process. This is called dimensional reduction. PCA has been performed for all 6 taps and in most of the cases it was possible to reduce dimensionality to 2 PCs (Eq. 1-2), explaining at the same time more than 80% percent of the variability [13].

\[
Y_1 = 0.25(A_1 + A_3 + A_5 + A_7) \\
Y_2 = 0.5(A_2 + A_6)
\]

(1)

(2)

In order to apply SPC, firstly an appropriated SPC control variable has to be selected. This variable will of course be a combination of the selected PCs after the PCA dimension reduction. Two well known statistics have been considered (the Hotelling T² and the Generalized Variance) and the last one gave the best results and it has been selected [14].

\[
GV = \left(\frac{(Y_{1,m} - \bar{Y}_{1,m})^2 + (Y_{2,m} - \bar{Y}_{2,m})^2}{n-1}\right)^{1/2}
\]

(3)

Where n is 2 (principal components) and m is learning period. There are several criteria to indicate the number of samples to be used in the SPC learning period but, after some trial and error tests, it was decided that the end of the learning period should be finished when the A2 parameter value would be equal to 1.8 times the average value of the five first tapped holes.

5. Experimental results in real time and the system program (Labview)

6 taps of the same characteristics has been tested and results are shown in Table 1. Second column indicates de total number of threads at which, an experienced operator declared that the tap end of life by catastrophic failure was close, and hence tap was changed. Third column indicates the number of tapped holes that passed the “go-no-go” gauge test. Therefore the difference between columns indicates the number of unacceptable threads. Fourth column is the quality thread (under/over dimension thread) and the fifth column indicates the place where are performed the tests.

<table>
<thead>
<tr>
<th>Tap</th>
<th>Total Threads</th>
<th>Correct threads</th>
<th>Quality thread</th>
<th>Factory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69</td>
<td>60</td>
<td>Oversized thread</td>
<td>Groupe Tivoly</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>174</td>
<td>Oversized thread</td>
<td>Groupe Tivoly</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>90</td>
<td>Oversized thread</td>
<td>Groupe Tivoly</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
<td>185</td>
<td>Undersized thread</td>
<td>Fagor Ederlan Factory</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>180</td>
<td>Undersized thread</td>
<td>Fagor Ederlan Factory</td>
</tr>
<tr>
<td>6</td>
<td>250</td>
<td>233</td>
<td>Undersized thread</td>
<td>Fagor Ederlan Factory</td>
</tr>
</tbody>
</table>

Before showing some display results, the monitoring system is described to understand how it works.

The system has three stages; first is Data Acquisition System where the torque is filtered and obtained, the second is the Data pre-processing System in which is calculated the areas and principal components and finally the third stage is Monitoring System which calculates the Generalized Variance and switch on/off the warning and alarm system.
**Figure 3.** Monitoring system of thread quality in Labview.

Groupe Tivoly.

Figure 4 and 5 show the GV control charts corresponding to taps 1 and 2, which are tested in Groupe Tivoly factory.

For instance, the GV chart (Figure 4) for tap 1 indicates an out of control alarm at tapped hole number 53. The last corrected thread occurs actually at thread number 60. Therefore, if seen as a classification device, the GV chart would have provided the equivalent of a 12% FP rate (threads that being OK are considered unacceptable). However, note how no unacceptable threads would have been machined with this tap.

**Figure 4.** Monitoring system Display when thread 69 is tapped for tap1. The red ligth was switch on in thread 53 (Groupe Tivoly).
Likewise, Figure 5 represents the GV for tap 2, the FP rate is only 4% (no FN’s, a FN consists on indicating that a thread is OK when it is not really).

*Figure 5. Monitoring system Display when thread 180 is tapped for tap2. The red ligth was switch on in thread 151 (Groupe Tivoly).*

Fagor Ederlan factory.

Figure 6 shows the GV control chart corresponding to tap 4, which are performed in Fagor Ederlan factory. The main goal of the GV chart is to be used on-line for process monitoring, without the need for inspecting the threads. Here, there is a problem because the production can not be stopped. Therefore, several taps are used in different batches; the first is new, the second has tapped 1000 threads, the third 2000 threads and the fourth 3000 threads (close to loss the dimensional quality).

For instance, the GV chart (Figure 6) for tap 4 indicates an out of control alarm at tapped hole number 175. The last corrected thread occurs actually at thread number 185. Therefore, if seen as a classification device, the GV chart would have provided the equivalent of an 6% FP rate. No defects.

*Figure 6. Monitoring system Display when thread 190 is tapped for tap 4. The red light was switch on in thread 175 (Fagor Ederlan factory).*
6. Conclusions

1. An on line monitoring system for assuring good quality of M10x1.25mm threads machined with TiCN Coated HSSE taps and using torque signals of the spindle motor has been developed and validated for cast iron GG25 plates and brake wheels (industrial environment). It does not give any false negative but it gives an average of 10% of false positives that increases tool costs. However the cost penalty in most cases can be assumed.

2. The monitoring system has performed in two different industrial environments (two types of machine tools). The results have been satisfactory.

3. The system detects when a particular tap goes out of control as a result of tool wear and it has enough generality to be applied to different types of work and tap materials with different cutting speeds, tap diameters and geometries and can replace the operator vigilance task keeping at the same time the threads quality.

7. Acknowledgments

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8. References