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An Experimental Investigation of the Effects of Spindle Speed Variation on Tool Wear in Turning

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Abstract

Spindle Speed Variation (SSV) is a well known technique to suppress regenerative chatter vibration both in turning and milling operations but a lack of knowledge regarding the effects of non stationary cutting conditions is still limiting its diffusion in the industrial scenario. In this paper an experimental study regarding the effects of Spindle Speed Variation technique on tool wear in steel turning is presented. The experimental tool wear tests were arranged and performed following a full factorial design: the cutting speed and the cutting speed modulation were the main investigated factors. The flank wear width was the main considered process response and it was monitored continuously during wear tests up to the end of the tool life. The effects of the factors were analyzed through the Analysis of Variance (ANOVA) approach.

Keywords: regenerative chatter; spindle speed variation; tool wear; turning

1. Introduction

In several production systems, when heavy and/or extensive machining operations are required, it is of paramount importance to maximize the Machine Material Removal Capability (MRC). The regenerative chatter mechanism occurrence (Altintas and Weck [1]), entailing high tool/workpiece vibrations, bad surface finishing quality and unacceptable tool wear rate, limits the achievable Material Removal Rate (MRR) and the overall machine tool productivity. The Stability Lobes Diagram (SLD), based also on tool/workpiece dynamic compliance evaluation, can be considered a useful instrument to maximize the chatter free depth of cut, i.e. Siddhpura and Paurobally in [2]. Spindle Speed Variation (SSV) is a well-known technique (Inamura and Sata, [3]) to suppress regenerative machine tool vibrations: the continuous modulation of the spindle speed breaks the energy injection that flows from the cutting process to the machine tool due the regenerative

effect thus avoiding the vibration growth. SSV is very promising, even comparing it with other chatter suppression technique (i.e. active solutions or tools with variable tool pitch for milling operations), basically due to its flexibility and the absence of additional devices. In the scientific literature, different modulating spindle laws (i.e. Yilmaz et. al [4] and Insperger et. al [5]) were analyzed evaluating both the cutting process stabilizing properties and the industrial feasibility, considering commercial Numerical Controls (NC) and spindle drives. Mainly for this last reason, the Sinusoidal Spindle Speed Variation (SSSV) seems to be the most promising implementation of the SSV: it involves, due to the function continuity, only finite acceleration values that are more easily processed and tracked by drives and NC. Although a lot of research effort was made over the years (Zatarin et. al [6] and Jaram et. al [8]), the technique is not widespread in real industrial applications, both in turning ([2]) and in milling. Different issues can represent potential limitations to the wide diffusion of the SSV. First of all, the lack of easy,

robust and recognized guidelines that can be used to select the most adequate SSSV parameters given a specific industrial application. Some literature works proposed methodologies to estimate SLD when SSV is implemented, for instance Insperger and Stepan [7] used the semi-discretization method to estimate chatter free regions in SSSV turning. Other researchers used time domain numerical models to predict the cutting performance during a non constant speed machining, i.e. Radulescu et. al in [9] and Zatarin et. al in [6]. Moreover, from the analysis of the specific literature, it can be stated that SSV seems more promising in turning operations, especially at low spindle speeds (compared to the main limiting eigenmode), rather than in milling operations. Despite a lot of research done up to now, there is still a lack of structured knowledge regarding the phenomena involved in the chip formation and in the spindle system when cutting conditions are not kept steady due to the need to modulate the spindle speed, [2]. For instance, it could be useful to estimate the thermal overload and the power consumption the electrical spindle motor is subjected to when the speed modulation is used. Moreover it could be interesting to understand what happens to the machined surface quality when the SSV is exploited: Albertelli et. al. in [10] performed some considerations on a few of these issues. Indeed, the research community should face a lot of unsolved matters in order to foster the further development of the technique also in an industrial context. Specifically, in this work an experimental analysis focused on tool wear mechanism in turning operations when the SSSV is adopted, is presented. The basic idea of the work is to understand if the SSSV can significantly decrease the life of the tool, compared to that observed using constant cutting speeds. The following scenario can thus be realistic: SSV allows a significant increase of the chatter free region permitting higher depths of cut over a wide range of cutting speeds. In order to be sure to avoid chatter vibration an operator could decide to use SSSV systematically. What will the operator have to expect regarding the life of the tool? To tackle this issue, in this work an experimental campaign was performed considering a steel turning application. The experimental tests were carried out following a factorial plan with replicates: the spindle speed and the SSSV are the analyzed factors. The tool flank wear was measured and monitored by means of a stereomicroscope during the overall cutting edge life and it represents the main process response. The temperature close to the cutting edge was also measured during some cutting tests. A statistical analysis of the experimental tests was also performed and presented. The design of experimental campaign and the involved methodologies are presented in section 2. In section 3 the experimental set-up and the results of some preliminary tests are

shown. In section 4 the experimental tests are analyzed and critically discussed. In section 5 conclusions of the work and interesting future activities are outlined.

Nomenclature

V_c　cutting speed [m/min]

Tl　Tool life [min]

D　bar diameter [mm]

L　bar length [mm]

Ω_0　nominal spindle speed

CSM: Constant Speed Machining

SSV: Spindle Speed Variation

SSSV: Sinusoidal Spindle Speed Variation

C_{max}: maximum spindle torque [rpm]

Ω_{lim}: maximum spindle speed [rpm]

DF: Degrees of freedom

SS: Sum of Square

MS: Mean Square

F: Fisher's test

P: p-value

RVA: dimensionless spindle speed modulation amplitude

RVF dimensionless spindle speed modulation frequency

f_z: feed rate [mm/rev]

p: radial depth of cut [mm]

VB_B: flank wear width [μm]

ml: cutting fluid flow [l/min]

CL: confidence level

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2. Design of Experiments and methodologies

In order to understand how the spindle speed modulation affects the life of a carbide tool an experimental campaign was designed. As explained in the previous section a realistic industrial scenario has been considered: a steel bar (UNI 7845-78 (255HB), D=130mm, L=385mm) has to be machined. As demonstrated in [10], for the typical steel cutting speeds and considering the main eigenmode within the 80-150Hz frequency range (typically linked to the tool dynamic behavior for the considered turning application), the SSSV can represent a valid instrument to suppress or prevent the regenerative chatter

occurrence. For instance, considering Eq. *(1)*, SSSV with RVA=0.3 (sinusoid amplitude/nominal spindle speed) and RVF=0.1 (sinusoid frequency/nominal spindle speed) guarantees a high magnification of the chatter free region and the overcoming of cutting performance limits due to the lathe dynamics, [7] and [10].

$$\Omega(t) = \Omega_0 \cdot \left(1 + RVA \cdot \sin\left(RVF \cdot \Omega_0 \cdot t\right)\right) \qquad (1)$$

In order to prevent any chatter vibration occurrence it could be useful to machine the bar using continuously the SSSV strategy. It is very interesting to understand if the spindle speed modulation strongly affects the tool wear mechanism entailing a shorter carbide life, compared to the Constant Speed Machining that implies the same MRR in the originally stable region (S), Fig. 1. Indeed, in the originally unstable region (U) of the SLD , it is expected that the spindle modulation positively affects the tool wear due to its stabilizing effects.
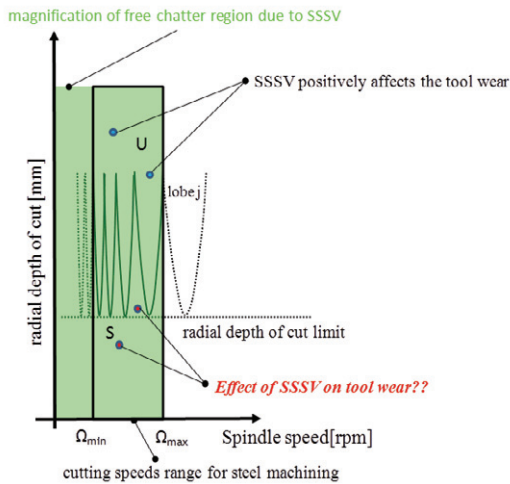

Fig. 1: SSSV effectiveness – scenario description

In order to tackle this issue an experimental approach has been adopted. The tool life tests were performed following a full factorial plan that considers two main factors, each with 2 levels:
- Cutting speed [$V_{c\,min}$/$V_{c\,max}$]
- Cutting condition [CSM/SSSV]

The flank wear average width (VB_B) is the main process response. The tool life tests were conducted following the standard IS0 3685:1993(E). A Stereomicroscope Optika SZN-T with Motic SMZ-168T support was used to measure flank wear width (VB_B) during the cutting tests. The flank wear width measurements were performed, as suggested in IS0 3685, in a straight region of the flank in-between the curved part and the region farthest away from the corner. This allowed to not consider the influence of both any

superficial residual stresses due to the previous cuts and the effect of the chip edge. Five flank wear width measurements had to be performed in the specified region to compute the average VB_B. For the performed cutting tests, the VB_B=0.3mm was used as the 'end of tool life' criteria. A carbide tool with a lead angle χ=90° was adopted (ISO standard code: TNMG220404-M5 5615 with Al2O3-TiCN coatings) and fixed on tool holder, ISO code MTJNL2525M22. Cutting fluid (oil-water emulsion) was used in order to reproduce realistic industrial machining conditions: it was adduced close to the cutting zone through a copper nozzle. The workpiece was mounted between the self-centering chuck and the tailstock, Fig. 2.
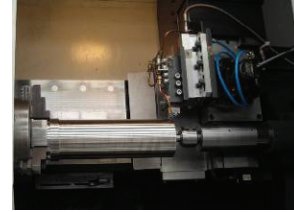

Fig. 2: Lathe, tool and workpiece used during tests

For the cutting tests performed with SSSV, a RVA=0.3/RVF=0.1 parameters combination was selected. The reason of this choice is related to the results reported in [11]: this modulation laws guarantees, for the considered turning application, an important magnification of the chatter free region over a wide range of spindle speeds ($\Omega_{min}(V_{cmin}) - \Omega_{max}(V_{cmax})$) for the considered limiting eigenfrequency range (80Hz-150Hz). It is therefore a SSSV parameters combination that could be used to prevent chatter occurrence in turning operations on different diameters. The other main cutting parameters are: $V_{c\,min}$=140m/min, $V_{c\,max}$=190m/min, radial depth of cut p=2mm, feed rate f_z=0.2mm/rev, RVA=0.3, RVF=0.1 and ml=2 l/min.

3. Set-up description and preliminary experimental tests

The lathe used (maximum available torque C_{max}=196Nm and maximum spindle speed Ω_{lim}=2525rpm) to perform cutting tests is equipped with an old analogical Numerical Control (NC). In order to implement the speed modulation on it, the speed control loop was bypassed; thus the speed reference signal was generated directly from an external computer and sent to the spindle motor drive. An acquisition board (National Instruments 6259) was used also to read the encoder signals and as an interface between the computer and the NC. The SSV technique can be more easily implemented on modern lathes. In order to be sure to rightly perform cutting tests with the selected RVA/RVF parameters combination over a wide range of workpiece diameters

(68mm-138mm), different preliminary cutting tests were performed. Basically, it was verified that both the available spindle torque and the spindle drive bandwidth are high enough to be able to follow the sinusoidal speed reference. Both data from the encoder and the currents absorbed by the spindle during SSSV machining were acquired in order to evaluate the spindle tracking performance. In order to prevent any undesired influences on the experimental campaign results, the material specifications were also checked: microhardness tests were performed along the machined bar radius as shown in Fig. 4.
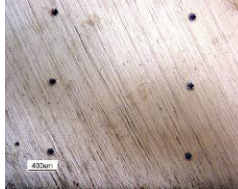
Fig. 3: microhardness tests performed on the workpiece

The ANOVA was performed on the microhardness tests data: the material hardness can be consider homogeneous along the bar radius. Some preliminary cutting tests were also performed in order to check the absence of undesired (i.e. due to regenerative chatter) vibration with each combination of the selected cutting parameters. In order to do that, during the performed cutting tests, tool vibrations and cutting forces were acquired and analyzed in order to check the lack of any frequency components linked to the lathe-tool dynamics that were previously experimentally investigated.

4. Experimental test results analysis

The tool wear cutting tests were performed following a randomized run order, as shown in Table 1.

Table 1: Tool wear test results

V_c [m/min]	SSV/CSM	Tl [min]
190	CSM	41.48
190	SSV	27.13
190	CSM	38.9
140	SSV	89.1
190	SSV	19.44
140	CSM	122.41
140	SSV	120.7
140	CSM	140.6

Considering the defined "end of life" criteria, the experimentation results are summarized in Table 1. The main effects plot (Fig. 4) roughly shows the influence of the studied factors on the life of the cutting edge. The interactions plot (Fig. 5) does not show evident

interaction between the two considered factors. Since different tests have to be performed, the family confidence interval was chosen as suggested by Bonferroni [11]: α_{fam}=15%.
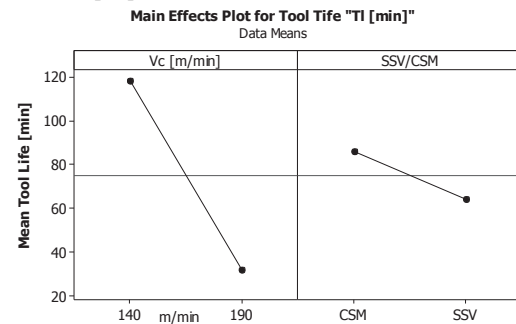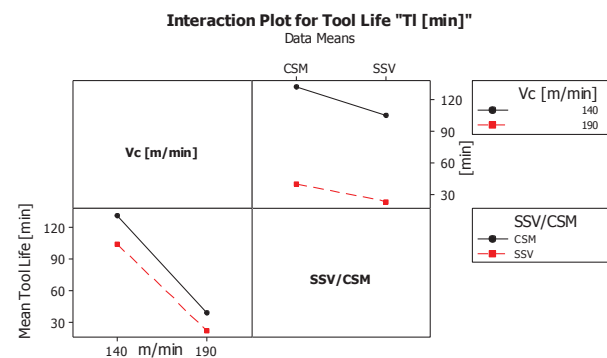

Fig. 4: Main Effects plot for the tool life

Fig. 5: Interaction plot for the tool life

Consequently, the confidence interval for each single test is α=5%. Considering the ANOVA results (Table 2), it can be inferred that only the cutting speed (V_c) affects the tool life Tl. The normality residuals assumption cannot be refused because the Anderson Darling's test gave p-value=0.99.

Table 2: ANOVA results, original data

Source	DF	SS	MS	F	P
V_c	1	14955.5	14955.5	85.72	0.001
CSM/SSV	1	946.7	946.7	5.43	0.08
Interaction	1	47.2	47.2	0.27	0.63
Error	4	697.9	174.5		
Total	7	16647.3			

Analyzing the residuals versus the observation order, it can be stated that independent residuals assumption cannot be also refused. Even if the test for equal variance (Bartlett's test) cannot lead to a homogeneity hypothesis refusal (p-Value=0.34), the residuals exhibit a possible cutting speed dependence, Fig. 6. In order to

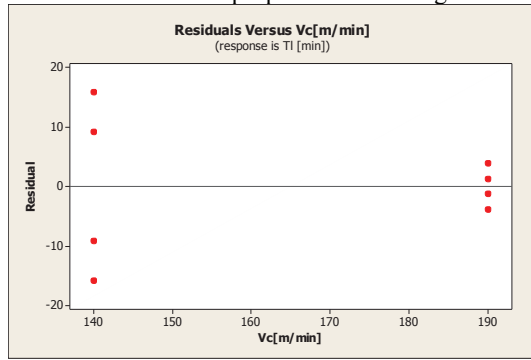perform further analysis a variance-stabilizing transformation has been proposed for the original data.

Fig. 6: Residuals Versus Cutting Speed

Considering both the Box-Cox power transformation suggestion (Lower CL=-0.57 and Upper CL=1.89) and the well known Taylor's equation, a logarithmic transformation (natural log) has been chosen. Performing again the ANOVA on the transformed data and not considering the cutting speed/SSSV interaction factor the following results have been obtained, Table 3:

Table 3: ANOVA results, transformed data (natural log)

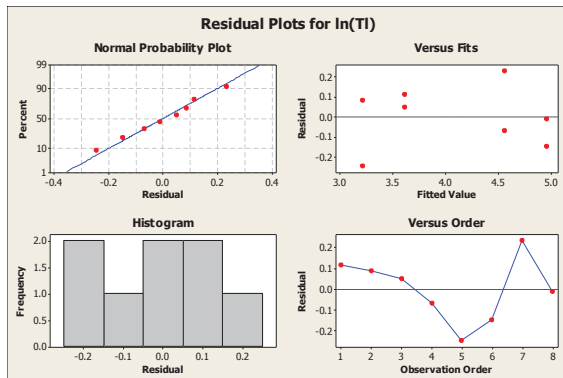| Source	DF	SS	MS	F	P
V_c	1	3.62188	3.62188	109.28	0
CSM/SSV	1	0.31532	0.31532	9.51	0.027
Error	4	0.16571	0.03314		
Total	7	4.10290			

Fig. 7: Residuals analysis, transformed data

The ANOVA hypotheses are still verified:
- Anderson-Darling's test p-value=0.99
- Bartlett's test p-Value=0.62
- Residual independency is verified

In order to fulfill the analysis, the power of the test can be computed. Fig. 8 shows the power trend considering the proposed experimental plan (2 factors-2 replicates) and various differences in any mean tool life that could be interesting to appreciate: i.e. 5%, 10%, 15%, 20%, 25%, 30%, 35%. These lead to the following test powers: 28%, 38%, 48%, 57%, 66%, 73%, 80%. A standard deviation σ=0.18min has been considered. For instance, if we are interested to appreciate a variation of the tool life equal to 15%, the probability to be able to rightly distinguish this situation is equal to 48%, that implies a quite high risk. This is mainly due to the low number of performed cutting tests.
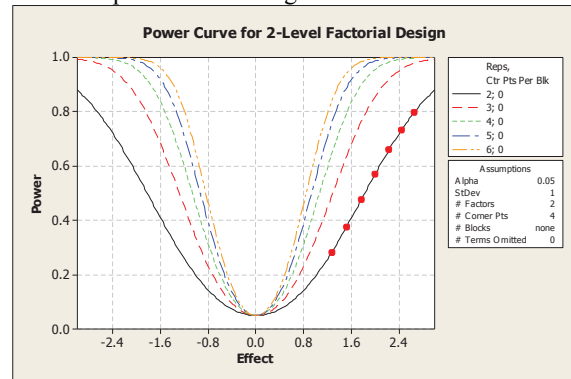

Fig. 8: Power of the test

Considering that the Fisher's (F) test p-value linked to SSSV/CSM factor is quite low even if the power of the test is not very high, it can be finally inferred that SSSV affects the life of the tool. To support the performed analysis, for each cutting condition, both the flank and crater wear at the end of the tool life tests are depicted in Fig. 9. It can be observed that the spindle speed modulation involved a different wear footprint (basically abrasion) on the tool even if the difference is less evident for the lower nominal cutting speed. The differences can be due to two different aspects: the continuous variation of the cutting edge engagement and the thermal stress the tool is subjected to during SSSV tests. In order to support the previous considerations the temperature close to the rake face was measured (sampling frequency 100Hz) for the adopted cutting conditions. To perform the temperature measurements, a thermocouple (0.5mm diameter) was fit into a hole in the carbide bit, as shown in Fig. 11. It can be observed (Fig. 12) that the temperature, measured close to point A, for the SSSV tests, shows a sinusoidal trend. It can be supposed that this effect is much more evident closer to the rake face. The wear rate increment, for the SSSV tests, could thus be linked to a temporarily reaching of higher temperature that could speed up the wear mechanisms.
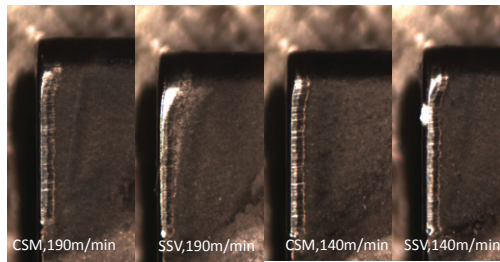
Fig. 9: flank wear at the end of the tool life, different cutting conditions
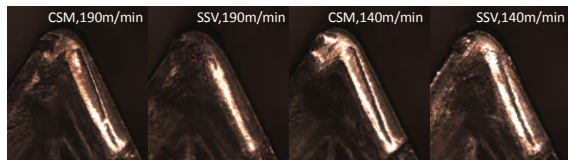

Fig. 10: crater wear at the end of the tool life, different cutting conditions
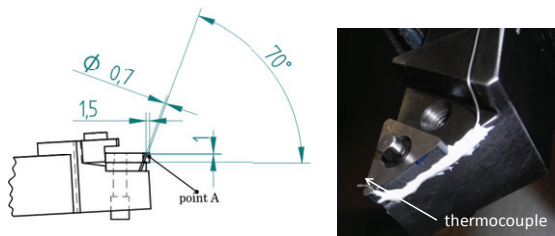

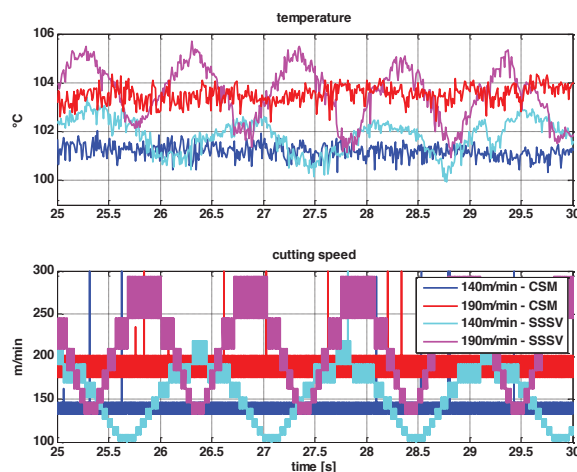Fig. 11: Thermocouple location inside the tool (point A)

Fig. 12: a) temperature(point A) measurement during cutting tests, b) cutting speed from spindle encoder

5. Conclusions and future works

In this paper, the effects of SSSV on tool wear in turning applications have been studied interpreting experimental cutting test results. The effects of two main factors were experimentally investigated: the cutting speed and the modulation of the cutting speed. The wear of the flank (main output response) was monitored during the cutting tests. The performed ANOVA showed that both the considered factors affect the flank wear. This is a quite interesting result: despite the SSSV does not change the MRR (neglecting for a while its potential stabilizing properties through the p increment) it reduces the tool life of the tool. This entails the need to create a model that, considering the involved phenomena, is able to predict the tool wear when SSSV is adopted. This model could be very useful to exploit and optimize the cutting speed modulation technique.

Acknowledgements

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