Engineering Transactions, **69**(4): 403–421, 2021, doi: 10.24423/EngTrans.1263.20211210
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
Université de Lorraine • Poznan University of Technology

Research Paper

Correlation Analysis between Tool Wear, Roughness and Cutting Vibration in Turning of Hardened Steel

Youcef ABIDI[1), 2)]*, Lakhdar BOULANOUAR[2)]

[1)] *Electrical Engineering Department, Freres Mentouri Constantin 1 University*
P.O Box 325, 25017 Constantine, Algeria
*Corresponding Author e-mail: abidiyoucef73@gmail.com

[2)] *LRTAPM, Badji Mokhtar University*
P.O Box 12, 23000 Annaba, Algeria

Hard machining is a process that has become highly recommended for replacing grinding in the manufacturing industry. This is due to its ability to machine complex shapes with reduced production costs by reducing the machining time and being an ecological process. Three technological parameters determine the quality and productivity generated from this process: cutting vibration, surface roughness and tool wear. Therefore, the analysis of the correlation between them is very important.

In the present investigation, the analysis of the correlation between cutting vibration, surface roughness and tool wear during a dry machining of hardened steel with a mixed ceramic tool is conducted in order to control these parameters online. This analysis is validated by developing predictive mathematical models.

To neutralize the effect of cutting parameters, a combination of parameters such as cutting speed, feed rate and depth of cut to be used in the experimental tests is selected from the literature based on a quality-productivity optimum performance. In the early stage, the effect of machining time on the three technological parameters is studied, then assessed by developing predictive mathematical models. In the second stage, an experimental and statistical analyses such as the Pearson and Spearman correlation methods are employed to determine correlations between tool wear, surface roughness and cutting vibration. Each parameter is compared with the other two. The models and their validations are developed using the Minitab 16 tool, and the predictions are obtained with desirable deviations.

The examination of the outcomes from the first stage reveals that the machining time has a significant effect on the three parameters. The regression models are found to be satisfactory in predicting each technological parameter. In the second stage, the results show a strong correlation between tool wear and cutting vibration, confirmed by the high Pearson and Spearman coefficients. The correlations between surface roughness and tool wear or the cutting vibration are strong only when the flank wear V_b is inferior 0.3 mm (which is required by the ISO standard). The regression models are developed with a desirable coefficient of regression (R^2). The novelty of this work lies in the fact that we consider the cutting vibration as a response generated the during cutting process and not as a variable affecting the other technological parameters. This was rarely studied in previous researches.

Key words: correlation; hard machining; cutting vibration; tool wear; surface roughness.

1. Introduction

Machining as a chip removal manufacturing process of hardened materials became highly recommended in the industry due to its productivity and qualitative contribution. It reduces production costs by around 30% compared to conventional machining [1], and improves the surface quality, which makes it competitive to grinding [2]. Therefore, it is a recommended economic and ecological process in the manufacturing industry. Although there are significant advances in the development of cutting tool materials such as ceramics, PCD and CBN, there is a great need to determine techniques for optimizing cutting processes. The primary recommendation by industry is to continuously improve quality processes and reduce the production cost with respect to the ecological environment [3]. Therefore, several investigations study the interaction between tool life, cutting parameters, tool geometry and machining environment.

In [4], many hardened steel grades have been combined and studied in the hard machining process. Furthermore, wear resistance of tool during machining of hardened steels was the main parameter studied by several researchers. For example, Benga and Abrao [5], in the hard machining of AISI 52100 steel with PCBN and ceramic tools, have shown that cutting speed is the main factor affecting tool life. The same results were obtained by other researchers [6–8].

Varaprasad *et al.* [9] found that, during the hard machining of the AISI D3 (62HRC) with ceramic CC6050, the depth of cut is the most influential parameter on the tool flank wear. Similar results were obtained in [10]. This proves that cutting parameters are not the only parameters affecting wear.

Shihab *et al.* [11] concluded in their review that tool wear was affected by tool geometry, the hardness of the workpiece and cutting parameters.

Wear modes observed in hard machining are abrasion, which is mainly influenced by cutting speed, and diffusion mode, which is influenced by the temperature gradient during cutting [5]. Usually, wear modes are affected by cutting speed [12]. Abrasive wear is generally the dominant mode during hard machining [4]. Typically, wear affects tool life and surface integrity obtained in hard machining [13, 14] and increases cutting force. The hardness of the cutting tool also has an important impact on tool life [15]. The wear modeling is very important for manufacturers. Therefore, several researchers have studied the modeling of cutting tool wear as well as its lifetime for different grades and cutting conditions [16–18]. Huang *et al.* [1] have given a general equation for tool wear (flank and crater) as a function of different machining parameters.

Minimum quantity lubrication in hard machining also plays an important role in improving tool life [19, 20], in addition to its ecological advantage.

The above review concerning the wear of tools supports the present research part, which focuses on the qualification of the ceramic tool for finishing turning of hardened steel. This wear study helps to determine tool life and choose the best cutting parameters that improve productivity and parts' quality.

The primary objective is to minimize machining time while maximizing quality, which translates into cost reduction [21]. Subsequently, most researches have invested more time in studying the optimization of machining processes. Therefore, we believe that surface quality is a very important technological parameter that needs continuous improvement. Surface roughness is affected by six major categories (Fig. 1) [22], which control cutting force and vibration, leading to the improvement of the machined surface quality. Tool's geometry, machined piece hardness, feed rate and cutting speed are the most influential parameters improving the surface roughness [23, 24], while feed rate was found to be the most influential in [25–29]. However, BHATTACHARYA *et al.* [30] found that the cutting speed is the most influential parameter on the surface roughness during machining of hardened AISI 1045 steel. The same result was also found by HAMDI *et al.* [31] for hard turning of 16MC5 steel. The roughness modeling is considered a major tool in the industry to optimize the parameters that improve the surface quality. Such a modeling has been a subject of various studies [32–36]. HESSAINIA *et al.* [36], in their work "On the prediction of surface roughness in the hard turning based on cutting parameters and vibration tool", used cutting parameters and cutting vibrations as variables on surface roughness. They found that the effect of axial and radial vibration on the surface roughness is minor in comparison to feed rate. A similar result was found in [37]. While UPADHYAY *et al.* [38] found that feed rate shows a maximum correlation with surface roughness followed by acceleration amplitude of vibration in the radial direction, depth of cut and acceleration amplitude of vibration in the tangential direction. In another work, PRASAD and BABU [39] found that the values of displacement amplitude of cutting vibration increase along with workpiece hardness level, depth of cut and cutting speed. A similar trend is observed in tool wear as well.

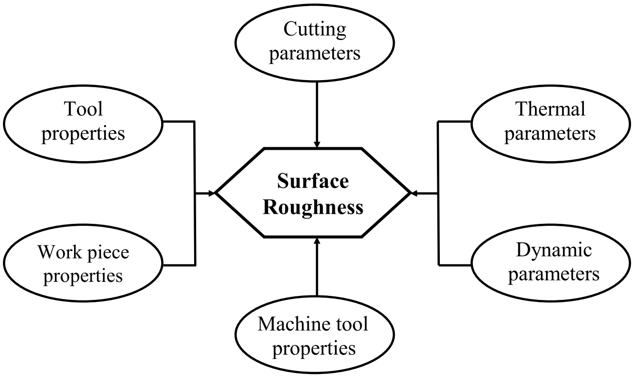

FIG. 1. Major categories affected surface roughness [21].

However, Abidi and Boulanouar [40] studied the effect of cutting parameters on cutting vibration evolution to correlate it with roughness generated simultaneously. They found that cutting speed has the most significant effect on the radial vibration, and the correlation between surface roughness and cutting vibration becomes low due to the instability of the machining system at high rotational frequencies. A similar result was found by Yousefi and Zohoor [41], who concluded that spindle speed has a contradictory effect on surface quality. This was due to generating additional parasitic vibrations during hard turning at high cutting speeds [18]. In the same context, Chuangwen *et al.* [42] found that when the cutting velocity is greater than 90 m/min, the vibration is increased due to the decrease in the rigidity of the high-speed cutting machine tool.

Recently, Azizi *et al.* [43] have found that the feed rate is the most important factor affecting the cutting tool radial vibration in hard turning at spindle speeds less than 500 rpm. A similar result was found by Keblouti *et al.* [44]. Ambhore *et al.* [45] developed mathematical models that predicted the cutting vibration in the three directions and roughness as a function of cutting parameters.

According to the presented above literature review, it can be concluded that improving tool life by optimizing cutting parameters should positively influence surface roughness. Consequently, in the present work, we investigate the correlation analysis between machining time and tool wear, surface roughness and cutting vibration. On the other hand, we study how, to reduce machining cost with the online control of the technological parameters such as tool wear, cutting vibration and surface roughness during turning of hardened steel AISI 1045. We investigate the correlation between them, excluding the effect of the parasitic vibrations mentioned in [18, 40, 41] by fixing a cutting regime and using the vibration as a response generated during the hard turning process and not as a variable declared, as it was done in previous researches. The novelty is the possibility of modeling each technological parameter in function to another after determining limit conditions. So, this work will answer the question: is there a practical possibility of knowing tool wear values and surface roughness values only from an online vibration record and not by stopping the machine operation and measuring these values?

2. Experimental materials and equipment

The turning experiments are carried out to obtain experimental data in the dry condition. A 6.6 kW Tos Trencin lathe type SN40 was used for the machining operations. The heat treatment is carried out using an electric oven type WOT 9703-457 404. Wear follow-up is conducted using an optical Hund (W-AD) microscope equipped with a digital display and a color charge-coupled device camera, enabling a precision of 0.001 mm to be obtained. Instantaneous roughness criteria measurements for each cutting condition are obtained using a Surftest 301 Mitutoyo roughness meter. It consists of a diamond point with a 5 μm radius and moves linearly on the machined surface. The length examined is 4 mm with a basic span of 0.8 mm. The measured values of arithmetic average of absolute roughness (R_a) are within the range 0.05 to 40 μm. A Vibration Digital Meter (VM-6360), measuring vibration velocity ranges from 0 to 199 mm/s, acceleration from 0 to 20 g and displacement from 1 to 1999 μm, is set to record vibration signals in the cutting tool. Radial vibrations are recorded by mounted a uni-axial accelerometer sensor on the tool holder in the radial direction. The experimental design flowchart is shown in Fig. 2. Cutting inserts are removable and provide eight squared working edges. Its ISO designation is SNGN 120408, commercially known as CC650 and it is made of mixed ceramics (70% Al_2O_3+ 30% TiC). Tool holders are codified as PSBNR2525M12 with the following geometry: $\chi r = 75°$, $\alpha = 6°$, $\gamma = -6°$, and $\lambda = -6°$.

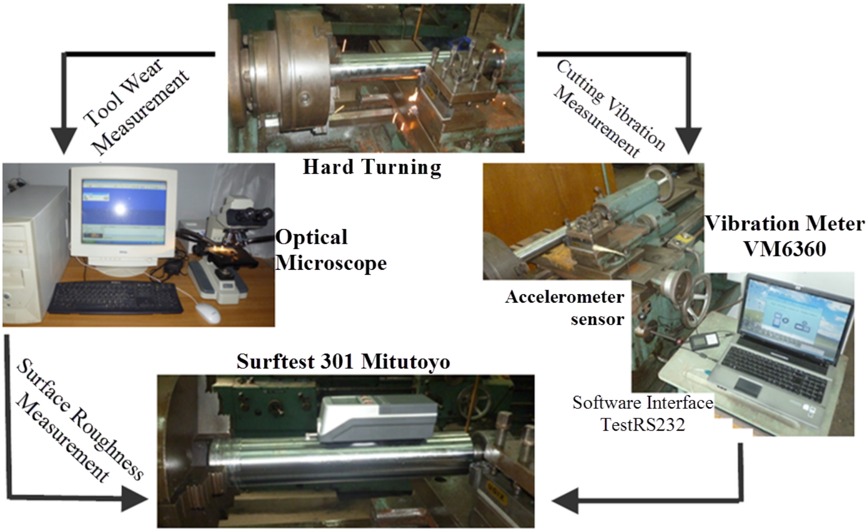

FIG. 2. The flowchart for modeling hard turning parameters.

2.1. Workpiece preparation

The AISI 1045 steel (C45 according to DIN) characterized by an important quenching ability is used. It is classified as non-alloy tool steel with good resistance to wear. It is commonly used in various mechanical engineering applications (molds for plastic material, and several pieces for the automotive sector: axles, gears, etc.). The chemical composition identified by an optical emission spectrometer (Thermo Scientific ARL 4460) is illustrated in Table 1.

Table 1. Chemical composition of grade AISI 1045 steel in weight %.

Designation	C	Mn	Si	Ni	Al	Cr	V	Ti	Mo
Steel of experiment	0.452	0.723	0.238	0.055	0.005	0.092	0.003	0.011	0.009

Hardening of the material is achieved for AISI 1045 steel rods with diameter and length of 60 and 350 mm, respectively, quenching treatment at 850°C in a water bath, followed by tempering at 200°C. Hardness values after tempering reach 40 HRC. Turning is performed without lubrication. The workpiece is mounted in between chuck and center.

2.2. Experimental design

The experimental work is divided into two parts. The first part is the analysis of the correlation between machining time and technological parameters (tool wear, surface roughness and cutting vibration) at cutting speed (V), feed rate (f) and depth of cut (D) equal to 200 m/min, 0.08 mm/rev, and 0.3 mm, respectively. This cutting regime is chosen from [40], which has been found to give the best surface quality and a good compromise between the cutting tool life, productivity and roughness [46]. Machining time is sequenced, and after a time increment. the maximum displacement wear is calculated, followed by the update of tool geometry. The results under the intermittent method are valid for a continuous cutting operation at the highest cutting speeds (beyond 150 m/min) [47]. Surface roughness measurements are directly measured on the same lathe without disassembling the turned workpiece in order to reduce uncertainties due to resumption operations. The measurements are repeated 3 times out of 3 generatrices equally positioned at 120° and the result is an average of these values. Error magnitude is globally estimated at around 10% for the obtained data, which is in agreement with the instrument characteristics and the experimental conditions. The radial vibration velocity of the cutting is recorded during the machining operation.

In the second part, we investigate the correlation between the technological parameters (wear, radial cutting vibration and surface roughness), two by two, using the correlation coefficients. Next, we suggest the models for each of them.

3. RESULTS AND DISCUSSION

3.1. Analysis of machining time effect on technological parameters

The first part of this investigation analyzes the machining time (t) effect on the cutting technological parameters (tool wear, surface roughness, and cutting vibrations) and presents the statistical study of the correlation between these three parameters.

The evolution of tool wear, the root-mean-square (RMS) amplitude value of vibration velocity in the radial direction (V_e) and the surface roughness (R_a, R_z and R_t) are presented in Table 2 and schematized in Fig. 3.

Table 2. Effect of machining time on flank wear, cutting vibration velocity and surface roughness ($V = 200$ m/min, $f = 0.08$ mm/rev, $D = 0.3$ mm).

	V_b [mm]	V_e [mm/s]	R_a [µm]	R_z [µm]	R_t [µm]
0.5	0.025	0.35	1.73	9.55	10.85
2.5	0.075	0.36	1.15	6.15	7.68
5.25	0.1	0.36	0.85	5.05	5.65
11	0.195	0.52	0.61	3.63	3.90
13	0.22	0.56	0.60	3.09	3.29
16.15	0.25	0.61	0.42	2.69	3.07
21.3	0.3	0.70	0.47	2.56	3.02
22.3	0.315	0.86	1.51	6.97	8.71

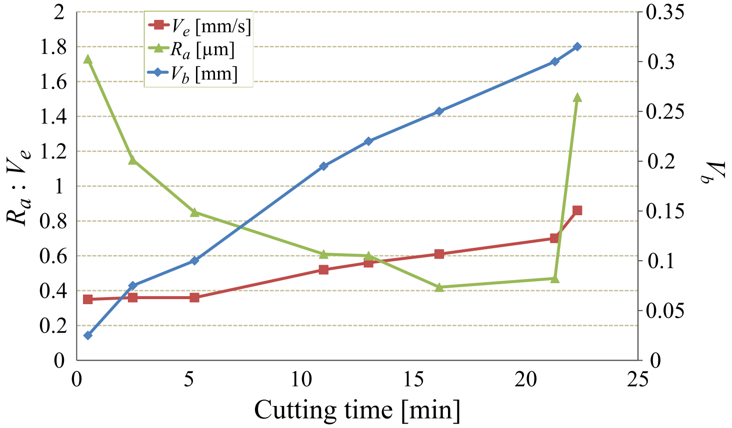

Fig. 3. Evolution of flank wear, cutting vibrations and surface roughness as a function of the cutting time.

3.1.1. Tool wear. The tool wear evolution is followed up to the permissible wear $[V_b] = 0.3$ mm for the cutting combination ($V = 200$ m/min, $f = 0.08$ mm/rev, $D = 0.3$ mm). During the cutting process, significant friction occurs between the cutting tool edge and chips [48] and between the major flank face and machined surface.

Figure 3 shows that the machining time has a destructive effect on the tool wear. The more the machining time increases, the more wear increases. As a result, a degradation of the tool nose occurs in the cavity form [46]. The flank wear (V_b) is more significant than the crater wear [18].

According to the experimental results in Table 2, the second-order simple regression model of wear as a function of machining time was developed at a 95% confidence level. The equation is given by:

$$V_b = 0.0205 + 0.018t - 0.000223t^2, \tag{3.1}$$

with: $R^2 = 99.7\%$. V_b is the flank wear [mm], and t is the machining time [min].

The analysis of variance (ANOVA) of regression using a software package MINITAB16 is shown in Table 3. The model is found statistically significant with a p-value (probability of significance) less than 0.05, where the predicted and measured values for both responses are very close to each other.

Table 3. ANOVA for flank wear (V_b) regression model.

Source	DF	SS	MS	F	p	Remarks
Regression	2	0.080329	0.040165	741.97	0.000	Significant
Residual Error	5	0.000271	0.000054			
Total	7	0.080600				

To check the model validity l, it is necessary to compare the predicted values (MR) with experimental ones. Figure 4 shows the corresponding graph for comparison of the MR and experimental values (ER) of flank tool wear. It is clear

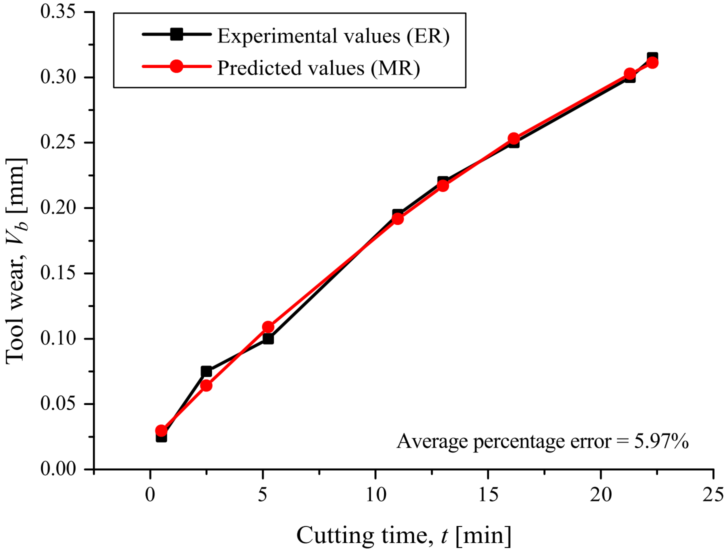

Fig. 4. Experimental (ER) and predicted (MR) values of flank wear (V_b) *versus* machining time.

that the two curves almost match. The obtained results are in good agreement with the experimental values. The average percentage error ($\%\delta$) is low, equal to 5.97%. This means that, within the tested range of input parameters, Eq. (3.1) can be used to predict tool wear value from machining time with minimal error.

3.1.2. Cutting vibration. Cutting vibration is an important technological parameter, which informs us about the dynamic characteristics of the manufacturing process during machining. The evolution of radial cutting vibration velocity is shown in Fig. 3. It is observed that the vibration velocity amplitudes (V_e) are quasi-constant during the first five minutes of machining, then they increase with a low rate up to 21st minute of machining, and then a remarkable acceleration is observed. In comparison to the tool wear evolution, we observe that during the first phase of tool degradation (break-in phase), vibration evolution is limited. Then, the tool wear evolution is revealed by a vibration growth. A similar phenomenon was observed by CHUANGWEN *et al.* [42].

The second-order regression model of the vibration as a function of the machining time is given by Eq. (3.2):

$$V_e = 0.334 + 0.00873t + 0.000551t^2 \tag{3.2}$$

with $R^2 = 95.5\%$.

The value of R^2 is very satisfactory.

The statistical significance of the model studied by ANOVA is shown in Table 4. The p-value (probability of significance) is less than 0.05.

Table 4. ANOVA for cutting vibration (V_e) regression model.

Source	DF	SS	MS	F	p	Remarks
Regression	2	0.22407	0.11204	53.20	0.000	Significant
Residual Error	5	0.01053	0.00211			
Total	7	0.23460				

Figure 5 shows the strong relationship between ER and MR. The average value of the error is small ($\delta = 4.9\%$). The absolute mean value of the error ($\%\ \delta$) is given by the formula:

$$\%\delta = \frac{\sum \left| \frac{\text{ER}-\text{MR}}{\text{ER}} \right|}{N} \cdot 100, \tag{3.3}$$

where N is the number of tests.

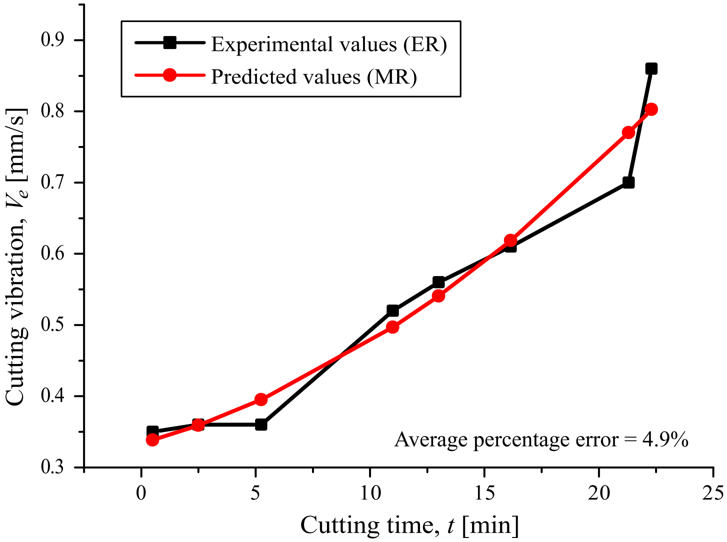

FIG. 5. ER and MR values for cutting vibration (V_e) *versus* machining time.

3.1.3. Surface roughness. Figure 3 shows that the surface roughness is maximum in the first machining stage and decreases progressively to reach a minimum level equivalent to $R_a = 0.42$ µm after 13 minutes of machining. Then, quasi-stable values are observed between 13 and 21 minutes. Next, the surface roughness sharply increases after 21 minutes and reaches $R_a = 1.51$ µm.

Compared to the tool wear, Fig. 3 shows that surface roughness is large during the break-in phase (first stage of machining). Then, in the second stage, when tool wear rate is low, roughness decreases to a minimum level and beyond the permissible wear ($[V_b] = 0.3$ mm). The main cutting edge of the tool undergoes rapid deterioration, which results in a degradation of the machined surface quality. We note that roughness values reached during the second stage are competitive to those produced by grinding machining.

Comparing the roughness criteria, Fig. 6 shows that the evolution of the roughness R_a, R_z and R_t corresponding to the arithmetic average of absolute roughness, the average maximum height of the roughness profile and the maximum height of the roughness profile, respectively – as a function of the machining time follows almost the same pattern. So the analysis will be limited to R_a.

The second-order simple regression model of the surface roughness as a function of the machining time is given by Eq. (3.4):

$$R_a = 1.72 - 0.193t + 0.00738t^2, \tag{3.4}$$

with: $R^2 = 71.1\%$.

The value of R^2 is acceptable.

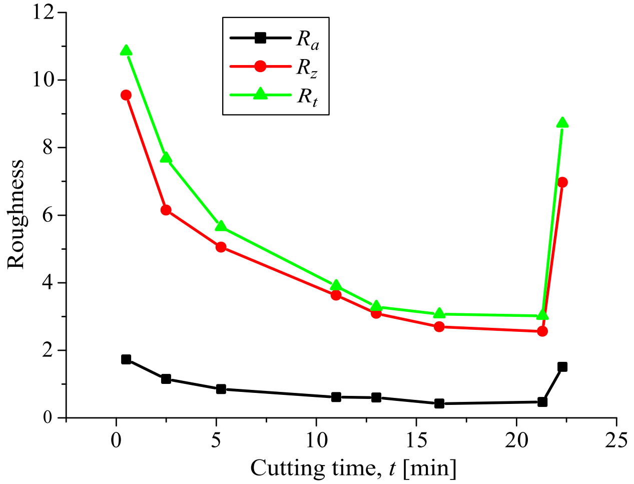

FIG. 6. R_a, R_z and R_t evolution as a function of the machining time ($V = 200$ m/min, $f = 0.08$ mm/rev, $D = 0.3$ mm).

The statistical significance of the model studied by ANOVA is shown in Table 5. The p-value is less than 0.05.

Table 5. ANOVA for surface roughness (R_a) regression model.

Source	DF	SS	MS	F	p	Remarks
Regression	2	1.21722	0.60861	6.14	0.045	Significant
Residual Error	5	0.49573	0.09915			
Total	7	1.71295				

3.2. Correlation between tool wear, surface roughness and cutting vibration

To achieve an online control of tool wear and machined surface roughness as a function of the cutting vibration, which is theoretically possible [49], we analyze the correlation between these technological parameters. So, the novelty of this study is an assumption that the cutting vibration variation is a response generated during the machining process, summary the variation of the roughness in twinning with the tool wear. In addition, for the correlation to become strong, we analyze it under the same cutting conditions to eliminate the effect of parasitic vibrations. The Pearson and Spearman coefficients are used to measure the linear or non-linear correlation between parameters to determine the modeling possibilities.

Figure 7 shows the graphic representation of the relationship between technological parameters: cutting tool wear (V_b), surface roughness (R_a) and cutting vibration (V_e), two by two.

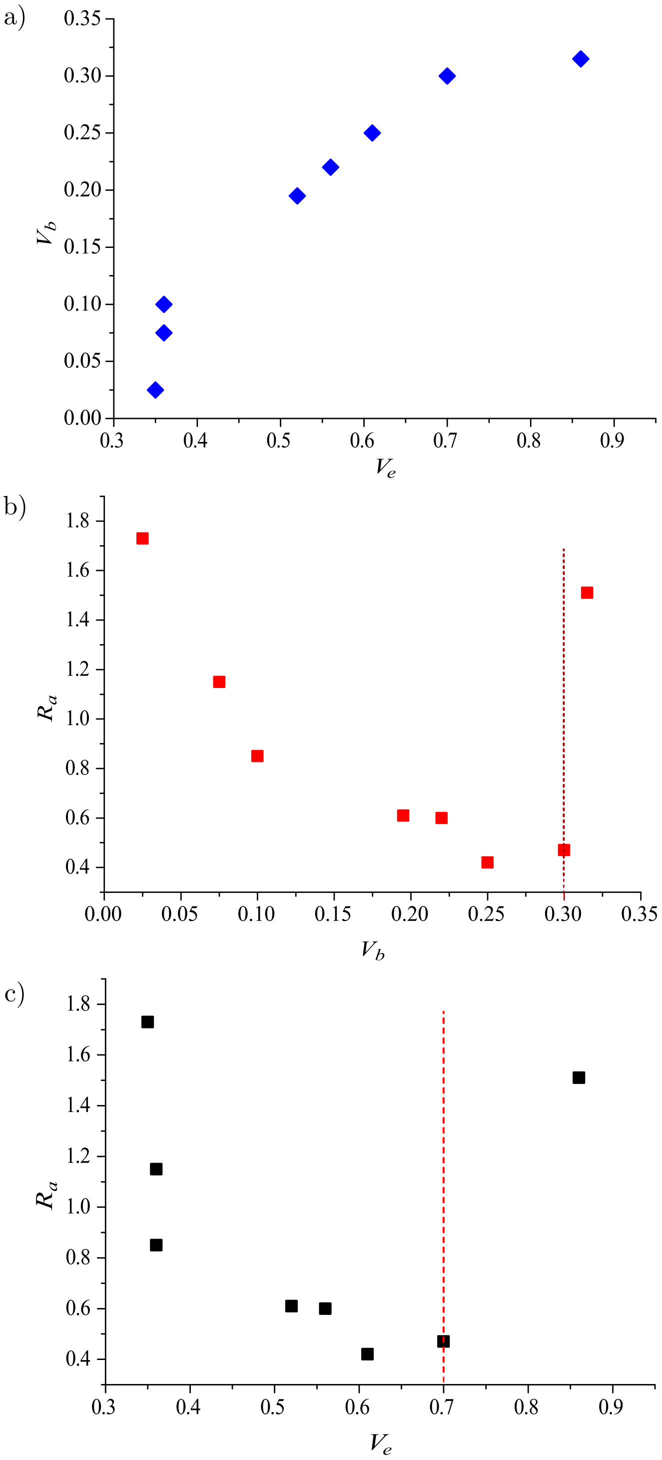

FIG. 7. The intensity of the relationships between technological parameters V_b, V_e and R_a.

3.2.1. Correlation between tool wear and cutting vibration. The correlation between flank wear V_b and cutting vibration (V_e) is positively strong, justified by the Pearson coefficient: $r = 0.948$, which is very close to 1. The probability p-value $= 0.000$ indicates that the correlation is significant. This correlation is also tested by the Spearman coefficient: $\rho = 0.988$, which again expresses the strong relationship between the two technological parameters (V_b and V_e).

According to Fig. 7a, cutting vibration constantly increases with the tool wear, this result is also found in [50, 42]. The point cloud graph shows the possibility of having a parabolic shape between V_b and V_e. This helps to develop a second-order regression model of the cutting tool wear (V_b) as a function of the cutting vibration (V_e), which is shown in Eq. (3.5):

$$V_b = 0.419 + 1.71V_e - 0.999V_e^2 \tag{3.5}$$

with: $R^2 = 97\%$.

The value of R^2 is very acceptable.

3.2.2. Correlation between surface roughness and tool wear. The analysis of the relationship $R_a = f(t, V_b)$ (Figs 3, 6 and 7b, and Table 2) shows that it is divided into two distinct parts:

Part 1: On the one hand, it can be observed that when the machining time increases from zero to 21.3 min, the tool wear reaches its allowable value $[V_b] =$ 0.3 mm. On the other hand, with increasing time and wear, the roughness criteria decrease from 1.73 to 0.47, 9.55 to 2.56, and 10.85 to 3.02 μ m, respectively for R_a, R_z and R_t (see Table 2).

Part 2: Beyond the allowable wear value $[V_b] = 0.3$ mm, tool collapse is catastrophic [46], which increases the contact surface between the tool and the workpiece and, thus, intensifying heating and cutting forces. This results in significant degradation of the machined surface.

Consequently, the analysis of the correlation between the roughness of the machined surface and tool wear will be limited to the first part, which corresponds to the lifetime of the tool required by ISO standards. This part is the most significant.

The correlation between R_a and V_b when V_b ≤ 0.3 mm: in Figs 3, 6 and 7b, we observe that when the machining time and wear V_b do not exceed 21.3 min and 0.3 mm, respectively, a very good correlation between R_a and V_b exists. In this interval, the Pearson correlation coefficient becomes $r = -0.913$ and the Spearman coefficient becomes $\rho = -0.964$, which shows that the relationship between roughness and flank wear is negatively strong. This is justified by the mathematical model deduced (3.6). The regression model of the workpiece surface roughness (R_a) presents a high determination of coefficient ($R^2 = 96.1\%$ very close to unity)

$$R_a = 1.92 - 11.6V_b + 22.9V_b^2 \tag{3.6}$$

with: $R^2 = 96.1\%$.

The value of R^2 is acceptable.

3.2.3. Correlation between surface roughness and cutting vibration. The strong correlations between surface roughness and tool wear in the $V_b \leq [V_b]$ interval, found in Subsec. 3.2.2, and between cutting vibration and wear, found in Subsec. 3.2.1, lead to testing the correlation between cutting vibration and surface roughness.

Statistical coefficients of the correlation between surface roughness and cutting vibration are $r = -0.81$ and $\rho = -0.95$, which shows that the relationship between them is negatively strong.

According to Fig. 7c, we see the possibility of having a parabolic shape between R_a and V_e when $V_b \leq [V_b]$. This is an advantage in developing a second-order regression model of the roughness (R_a) as a function of the cutting vibration (V_e), which is shown in Eq. (3.7):

$$R_a = 4.47 - 12.5V_e + 9.64V_e^2 \tag{3.7}$$

with: $R^2 = 72.8\%$.

The value of R^2 is acceptable.

4. Conclusions

The present work is a contribution in determining the correlations between surface roughness, tool wear and tool radial vibration when turning hardened AISI 1045 steel (40 HRC) using the mixed ceramic (70% Al_2O_3+30% TiC). The effect of machining time on the three technological parameters such as tool wear, surface roughness and cutting vibration was first investigated to see if there is relationship between these three parameters' behaviors. Then, the correlation between them was studied. The following was found:

- Machining time has a great influence on the cutting tool edge wear.
- Increasing machining time increased the cutting tool wear and cutting vibrations.
- Strong negative correlation between surface roughness and machining time in $V_b < 0.3$ mm interval was observed.
- Increased tool wear during machining negatively affected the quality of the machined surface and increased cutting vibration.
- The best surface quality and machining stability were obtained during the tool life ($V_b < 0.3$ mm). The relationships between machining time

and technological parameters (tool wear (V_b), cutting vibration (V_e) and machined surface roughness (R_a)) are expressed by multiple quadratic regression models, which can be used to estimate the expressed values of the performance level during machining. The regression models produced a desirable determination of coefficient (R^2). This confirms that there are correlations between the three technological parameters.

- Above $V_b = 0.3$ mm, wear accelerated fast, cutting stability declined (vibrations) and surface quality deteriorated considerably. A strong correlation between tool wear and cutting vibration was observed. The relationship between them expressed by the regression model presented a high determination coefficient (R^2).
- An inversely strong correlation between roughness and wear was observed when the allowable value ($V_b = 0.3$ mm) was not exceeded. The regression model was determined and presented a high determination coefficient (R^2).
- An inversely strong correlation between roughness and vibration during machining before the tool life limit (tool life equivalent to $V_b = 0.3$ mm) was observed. The regression model was determined and presented an acceptable determination coefficient (R^2).
- Contrary to the previous research, this investigation shows that there is a possibility of modeling each technological parameter in relationship to others if limit conditions are defined and machining does not generate parasitic vibrations.
- Relationships between V_b or R_a and V_e were presented. They allowed tool wear or surface roughness follow-up from easily accessible cutting vibration data. This is a very significant issue for automated monitoring of industrial machining processes.
- This work demonstrates that the online prediction of surface roughness or tool wear using cutting vibration values during machining without stopping the machine is possible. Therefore, it is possible to achieve computer-controlled machining in a flexible manufacturing system.

References

1. Huang Y., Chou Y.K., Liang S.Y., CBN tool wear in hard turning: A survey on research progresses, *The International Journal of Advanced Manufacturing Technology*, **35**: 443–453, 2007, doi: 10.1007/s00170-006-0737-6.

2. M'Saoubi R., Outeiro J.C., Chandrasekaran H., Dillon Jr. O.W., Jawahir I.S., A review of surface integrity in machining and its impact on functional performance and life of machined products, *International Journal of Sustainable Manufacturing*, **1**(1–2): 203–236, 2008, doi: 10.1504/IJSM.2008.019234.

3. Govindan P., Vipindas M.P., Surface quality optimization in turning operations using Taguchi method – A review, *International Journal of Mechanical Engeneering and Robotics Research*, **3**(1): 89–118, 2014, http://www.ijmerr.com/v3n1/ijmerr_v3n1_11.pdf.
4. Chinchanikar S., Choudhury S.K., Machining of hardened steel – Experimental investigations, performance modeling and cooling techniques: A review, *International Journal of Machine Tools & Manufacture*, **89**: 95–109, 2015, doi: 10.1016/j.ijmachtools.2014.11.002.
5. Benga G.C., Abrao A.M., Turning of hardened 100Cr6 bearing steel with ceramic and PCBN cutting tools, *Journal of Materials Processing Technology*, **143–144**: 237–241, 2003, doi: 10.1016/S0924-0136(03)00346-7.
6. Attanasio A., Umbrello D., Cappellini C., Rotella G., M'Saoubi R., Tool wear effects on white and dark layer formation in hard turning of AISI 52100 steel, *Wear*, **286–287**: 98–107, 2012, doi: 10.1016/j.wear.2011.07.001.
7. Motorcu A.R, Tool life performances, wear mechanisms and surface roughness characteristics when turning austenised and quenched AISI 52100 bearing steel with ceramics and CBN/TIC cutting tools, *Indian Journal of Engineering & Materials Science*, **18**(2): 137–146, 2011, http://nopr.niscair.res.in/handle/123456789/11682.
8. Fnides B., Boutabba S., Fnides M., Aouici H., Yallese M.A., Tool life evaluation of cutting materials in hard turning of AISI H11, *Estonian Journal of Engineering*, **19**(2): 143–151, 2013, doi: 10.3176/eng.2013.2.04.
9. Varaprasad B.H., Srinivasa R.C., Vinay P.V., Effect of machining parameters on tool wear in hard turning of AISI D3 steel, *Procedia Engineering*, **97**: 338–345, 2014, doi: 10.1016/j.proeng.2014.12.257.
10. Gaitonde V.N., Karnik S.R., Figueira L., Davim J.P., Machinability investigations in hard turning of AISI D2 cold work tool steel with conventional and wiper ceramic inserts, *International Journal of Refractory and Hard Materials*, **27**(4): 754–763, 2009, doi: 10.1016/j.ijrmhm.2008.12.007.
11. Shihab S.K., Khan Z.A., Mohammad A., Siddiquee A.N., A review of turning of hard steels used in bearing and automotive applications, *Production & Manufacturing Research*, **2**(1): 24–49, 2014, doi: 10.1080/21693277.2014.881728.
12. De Godoy V.A.A., Diniz A.E., Turning of interrupted and continuous hardened steel surfaces using ceramic and CBN cutting tools, *Journal of Materials Processing Technology*, **211**(6): 1014-1025, 2011, doi: 10.1016/j.jmatprotec.2011.01.002.
13. Kumar C.S., Patel S.K., Experimental and numerical investigations on the effect of varying AlTiN coating thickness on hard machining performance of Al_2O_3-TiCN mixed ceramic inserts, *Surface and Coatings Technology*, **309**: 266–281, 2017, doi: 10.1016/j.surfcoat.2016.11.080.
14. Hosseini S.B., Ryttberg K., Kaminski J., Klement U., Characterization of the surface integrity induced by hard turning of bainitic and martensitic AISI 52100 steel, *Procedia CIRP*, **1**: 494–499, 2012, doi: 10.1016/j.procir.2012.04.088.
15. Okada M., Hosokawa A., Tanaka R., Ueda T., Cutting performance of PVD-coated carbide and CBN tools in hardmilling, *International Journal of Machine Tools and Manufacture*, **51**(2): 127–132, 2011, doi: 10.1016/j.ijmachtools.2010.10.007.
16. Yallesse M.A., Boulanouar L., Belhadi S., Investigation de l'usure de deux matériaux à outils à base d'alumine SiCw et de CBN-TiCN lors de l'usinage d'un acier

à roulements 60HRC, *Sciences & Technologie B*, **20**: 92–99, 2003, http://revue.umc.edu.dz/index.php/b/article/view/1264.

17. Sahoo A.K., Sahoon B., Experimental investigations on machinability aspects in finish hard turning of AISI 4340 steel using uncoated and multilayer coated carbide inserts, *Measurement*, **45**(8): 2153–2165, 2012, doi: 10.1016/j.measurement.2012.05.015.

18. Abidi Y., Boulanouar L., Amirat A., Experimental study on wear of mixed ceramic tool and correlation analysis between surface roughness and cutting tool radial vibrations during hard turning of AISI 52100 steel, *Journal of Engineering Science and Technology*, **13**(4): 943–963, 2018, http://jestec.taylors.edu.my/Vol%2013%20issue%204%20April%202018/13_4_8.pdf.

19. Sidik N.A.C., Samion S., Ghaderian J., Afiq M.N., Yazid W.M., Recent progress on the application of nanofluids in minimum quantity lubrication machining: A review, International *Journal of Heat and Mass Transfer*, **108**(Part A): 79–89, 2017, doi: 10.1016/j.ijheatmasstransfer.2016.11.105.

20. Benardos P.G., Vosniakos G.C., Predicting surface roughness in machining: a review, *International Journal of Machine Tools and Manufacture*, **43**(8): 833–844, 2003, doi: 10.1016/S0890-6955(03)00059-2.

21. Khorasani A.M., Yazdi M.R.S., Safizadeh M.S., Analysis of machining parameters effects on surface roughness: a review, International Journal of Computational Materials Science and Surface Engineering, **5**(1): 69-84, 2012, doi: 10.1504/IJCMSSE.2012.049055.

22. Dilbag S.P., Venkateswara R., A surface roughness prediction model for hard turning process, *The International Journal of Advanced Manufacturing Technology*, **32**: 1115–1124, 2007, doi: 10.1007/s00170-006-0429-2.

23. Özel U., Hsu T.K., Zeren E., Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel, *The International Journal of Advanced manufacturing Technology*, **25**: 262–269, 2005, doi: 10.1007/s00170-003-1878-5.

24. Sahin Y.A., Motorcu A.R., Surface roughness model in machining hardened steel with cubic boron nitride cutting tool, *International Journal of Refractory Metals and Hard Materials*, **26**(2): 84–90, 2008, doi: 10.1016/j.ijrmhm.2007.02.005.

25. D'Addona D.M., Raykar S.J., Analysis of surface roughness in hard turning using wiper insert geometry, *Procedia CIRP*, **41**: 841–846, 2016, doi: 10.1016/j.procir.2015.12.087.

26. Rajeev D., Dinakaran D., Kanthavelkumaran N., Austin N., Experimental study of surface roughness in hard turning of AISI4140 steel with coated carbide tool, *World Applied Sciences Journal*, **34**(10): 1310–1317, 2016, doi: 10.5829/idosi.wasj.2016.1310.1317.

27. Bouacha K., Yallese M.A., Mabrouki T., Rigal J.F., Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool, *International Journal of Refractory Metals and Hard Materials*, **28**(3): 349–361, 2010, doi: 10.1016/j.ijrmhm.2009.11.011.

28. Asiltürk I., Akkuş H., Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method, *Measurement*, **44**(9): 1697–1704, 2011, doi: 10.1016/j.measurement.2011.07.003.

29. Yallesse M.A., Rigal J.F., Chaoui K., Boulanouar L., The effects of cutting conditions on mixed ceramic and cubic boron nitride tool wear and on surface roughness

during machining of X200Cr12 Steel (60 HRC), *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, **219**(1): 35–55, 2005, doi: 10.1243/095440505X8082.

30. Bhattacharya A., Das S., Majumder P., Batish A., Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA, *Production Engineering*, **3**: 31–40, 2009, doi: 10.1007/s11740-008-0132-2.

31. Hamdi A., Merghache S.M., Aliouane T., Effect of cutting variables on bearing area curve parameters (BAC-P) during hard turning process, *Archive of Mechanical Engineering*, **67**(1): 73–95, 2020, doi: 10.24425/ame.2020.131684.

32. Meddour I., Yallese M.A., Khattabi R., Elbah M., Boulanouar L., Investigation and modeling of cutting forces and surface roughness when hard turning of AISI 52100 steel with mixed ceramic tool: cutting conditions optimization, *The International Journal of Advanced Manufacturing Technology*, **77**: 1387–1399, 2015, doi: 10.1007/s00170-014-6559-z.

33. Bartarya G., Choudhury S.K., Effect of cutting parameters on cutting force and surface roughness during finish hard turning AISI52100 grade steel, *Procedia CIRP*, **1**: 651–656, 2012, doi: 10.1016/j.procir.2012.05.016.

34. Das S.R., Kumar A., Dhupal D., Effect of machining parameters on surface roughness in machining of hardened AISI 4340 steel using coated carbide inserts, *International Journal of Innovation and Applied Studies*, **2**(4): 445–453, 2013, https://core.ac.uk/reader/25718000.

35. Agrawal A., Goel S., Rashid W.B., Price M., Prediction of surface roughness during hard turning of AISI 4340 steel (69 HRC), *Applied Soft Computing*, **30**: 279–286, 2015, doi: 10.1016/j.asoc.2015.01.059.

36. Hessainia Z., Belbah A., Yallese M.A., Mabrouki T., Rigal J.F., On the prediction of surface roughness in the hard turning based on cutting parameters and tool vibrations, *Measurement*, **46**(5): 1671–1681, 2013, doi: 10.1016/j.measurement.2012.12.016.

37. Sarnobat S.S., Raval H.K., Prediction of surface roughness from cutting tool vibrations in hard turning of AISI D2 steel of different hardness with conventional and wiper geometry CBN inserts, *Journal of Applied Mechanical Engineering*, **7**(1): 1–7, 2018, doi: 10.4172/2168-9873.1000300.

38. Upadhyay V., Jain P.K., Mehta N.K., In-process prediction of surface roughness in turning of Ti–6Al–4V alloy using cutting parameters and vibration signals, *Measurement*, **46**(1): 154–160, 2013, doi: 10.1016/j.measurement.2012.06.002.

39. Prasad B.S., Babu M.P., Correlation between vibration amplitude and tool wear in turning: Numerical and experimental analysis, *Engineering Science and Technology, an International Journal*, **20**(1): 197–211, 2017, doi: 10.1016/j.jestch.2016.06.011.

40. Abidi Y., Boulanouar L., Analyse de la correlation entre la rugosité et la vibration de coupe en usinage des aciers durcis, *U.P.B. Scientific Bulletin Series D*, **79**(4): 157–170, 2017, https://www.scientificbulletin.upb.ro/rev_docs_arhiva/fullc17_730627.pdf.

41. Yousefi S., Zohoor M., Experimental studying of the variations of surface roughness and dimensional accuracy in dry hard turning operation, *The Open Mechanical Engineering Journal*, **12**: 175–191, 2018, doi: 10.2174/1874155X01812010175.

42. Chuangwen X., Jianming D., Yuzhen C., Huaiyuan L., Zhicheng S., Jing X., The relationship between cutting parameters, tool wear, cutting force and vibration, *Advance in Mechanical Engineering*, **10**(1): 1–14, 2018, doi: 10.1177/1687814017750434.

43. Azizi M.W., Keblouti O., Boulanouar l., Yallese M.A., Design optimization in hard turning of E19 alloy steel by analysing surface roughness, tool vibration and productivity, *Structural Engineering and Mechanics*, **73**(5): 501–513, 2020, doi: 10.12989/sem.2020.73.5.501.

44. Keblouti O., Boulanouar L., Azizi M.W., Bouziane A., Multi response optimization of surface roughness in hard turning with coated carbide tool based on cutting parameters and tool vibration, *Structural Engineering and Mechanics*, **70**(4): 395–405, 2019, doi: 10.12989/sem.2019.70.4.395.

45. Ambhore N., Kamble D., Chinchanikar S., Evaluation of cutting tool vibration and surface roughness in hard turning of AISI 52100 steel: an experimental and ANN approach, *Journal of Vibration Engineering & Technologies*, **8**: 455–462, 2020, doi: 10.1007/s42417-019-00136-x.

46. Abidi Y., Analysis of the compromise between cutting tool life, productivity and roughness during turning of C45 hardened, *Production Engineering Archives*, **27**(1): 30–35, 2021, doi: 10.30657/pea.2021.27.4.

47. Thomas J.L., Lambert B.K., Intermittent versus continuous cutting methods of tool life testing, *International Journal of Production Research*, **2**(3): 283–289, 1963, doi: 10.1080/00207547208929927.

48. Abidi Y., Relationship between surface roughness and chip morphology when turning hardened steel, *Production Engineering Archives*, **26**(3): 92–98, 2020, doi: 10.30657/pea.2020.26.19.

49. Dong D.Y., Choi Y.G., Kim H.G., Hsiac A., Study of the correlation between surface roughness and cutting vibrations to develop an on-line roughness measuring technique in hard turning, *International Journal of Machine Tools and Manufacture*, **36**(4): 453–464, 1996, doi: 10.1016/0890-6955(95)00074-7.

50. Pourmostaghimi V., Zadshakoyan M., Sadeghi M.H., Vibration based assessment of tool wear in hard turning using wavelet packet transform and neural networks, *International Journal Advanced Design and Manufacturing Technology*, **12**(2): 17–26, 2019, http://admt.iaumajlesi.ac.ir/article_668451_fc854b055c569088e9c8b8f5123e91f8.pdf.

Received October 4, 2020; accepted version November 15, 2021.