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# Statistical analysis and modelization of tool life and vibration in dry face milling of AISI 52100 STEEL in annealed and hardened conditions

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**Abstract.** The objective of the present work is to investigate the effect of cutting parameters (Vc, fz and ap) on tool life and the level of vibrations velocity in the machined part during face milling operation of hardened AISI 52100 steel. Dry-face milling has been achieved in the annealed (28 HRc) and quenched (55 HRc) conditions using multi-layer coating micro-grain carbide inserts. Statistical analysis based on the Response surface methodology (RSM) and ANOVA analysis have been conducted through a plan of experiments methodology using a reduced Taguchi table (L9) in order to obtain engineering models for tool life and vibration velocity in the workpiece for both heat treatment conditions. The results show that the cutting speed has a dominant influence on tool life for both soft and hard part. Cutting speed and feed per tooth is the most significant parameters for vibration levels. Comparing the experimental values with those predicted by the developed engineering models of tool life and levels of vibrations velocity, a good correlation has been obtained (between 97% and 99%) in annealed and hard conditions.

**Keywords:** machinability; vibration; AISI52100 Steel; tool life; wear; modeling

## 1. Introduction

Hard machining as an alternative for substituting grinding is very attractive for high precision mechanical components requiring high resistance to wear and fatigue. For instance, the comprehension of the machinability of AISI 52100 steel is always the subject of research.

The comprehension of the behavior of 52100 steel parts during their operation is still relevant because of the increasingly demanding conditions of use, their performance and their resistance to wear and fatigue. The machining of this steel greatly contributes to this desired behavior. Therefore researchers are always directed towards the machinability of 52100 steel, taking into account new cutting materials, machining conditions and cutting regimes and new machining technologies. For instance, hard machining as an alternative for substituting grinding is very attractive in industries but it is not so evident because the cutting parameters and conditions should be optimized. How to achieve this is the matter of many researchers from all over worldwide machining industry.

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Considering hard turning, recently, Alok and Das (2019) have explored through X-ray disfraction and XRD analysis, the effect of white layer on hard turned AISI 52100 steel with the fresh tip of newly developed HSN2 coated insert. They have reported that the thickness of white layer reduces with increased cutting speed. Paturi *et al*. (2018) have suggested two statistical methods, the application of regression and artificial neural network analyses for modeling surface roughness in hard turning of AISI 52100 steel. They have predicted roughness models in good agreement with experimental results. Umamaheswarrao *et al*. (2018) have presented a very interesting paper that suggests multi-objective optimization for a hard turning of AISI 52100 steel to provide optimum surface quality, machining force and work piece surface temperature. Siraj *et al*. (2018) have presented the modeling of roughness value from tribological parameters in hard turning of 52100 steel using different tool nose radius. Through Taguchi method and linear regression method they have found that the tool nose radius is more affecting surface roughness than tribological, parameters. Pawar *et al*. (2017) have modeled the effect of cutting parameters on induced residual stresses in machined surface during hard turning of 52100 steel using ABAQUS/CAE 14.0 software. They have reported that as cutting speed or feed rate increases tensile residual stresses increases. AISI 52100 Steel is melted in an electric furnace and forged or hot rolled. It is often recommended for applications that require high resistance to wear and contact fatigue when considering heat treatments. Basu *et al*. (2012) have explored the typical as-received annealed steel in unimplanted condition. one examining the microstructures it showed uniformly distributed spherodised carbides in the ferrite matrix are evident and in tempered steel the martensitic matrix. In his recent studies have shown that the mechanical properties of 52100 steel can be improved by isothermal heat treatments such as bainitic quenching. This steel is commonly used in the quenched and tempered states with a predominantly martensitic microstructure that provides abrasion resistance and adequate mechanical properties at room temperature.

In recent years, Chouldhury and El-Baradie (1998), Cakir *et al*. (2009), Aouici *et al*. (2012) and Slaimia *et al*. (2017) presented a various statistical and experimental studies have been carried out on the basis of design and analysis experimental methods for determining the effects of cutting parameters on machinability of different materials. Alauddin *et al*. (1997), Chomsamutr and Jongprasithporn (2012) and Aouici *et al*. (2014) have shown that response surface methodology (RSM) is one of the most used methods, it is a set of mathematical and statistical techniques useful for modeling and analyzing problems in whose response is influenced by several variables. Several studies have applied the RSM in different machining operations (turning, milling, and drilling), mathematical modeling and analysis of variance (ANOVA) allow to determine the influence of each cutting parameter and its contribution on the response surface. Cakir *et al*. (2009), examined the effect of cutting parameters (cutting speed, feed rate and depth of cut) on the surface roughness through the mathematical model developed by using the data gathered from a series of turning experiments. An additional investigation was carried out in order to evaluate the influence of two well-known coating layers on the surface roughness. Choudhury and El-Baradie (1998) formulated a mathematical model for flank wear, and concluded that the cutting velocity (speed) and the index of diffusion coefficient were the most significant factors, followed by the feed and depth of cut. M. Alauddin *et al*. (1997), Abou-El-Hossein *et al*. (2007), Confirmed in their study that carbide cutting tools are widely used in metal cutting industry for cutting various hard materials such as, alloy steels, die steels, high speed steels, bearing steels, white cast iron and graphite cast iron. Da Silva *et al*. (2011) have stated that the use of coated tools are becoming increasingly demanding among the other tool materials. More than 40% of all cutting tools are coated in modern industry today. The feasibility of dry cutting in the material removal industries has received much attention due to high cost of cutting fluids, at 17% of the total manufacturing cost. Cutting fluid waste needs to be treated prior to disposal and prolonged exposure is hazardous to the machine operators due to risks of skin cancer and breathing difficulties. Dry cutting is desirable because not only it reduces manufacturing cost but also eliminates all the adverse negative effects associated with the usage of cutting fluids for cooling and lubricating purposes.

In recent year, Benghersallah *et al*. (2018) have presented a contribution in characterizing end milling process of annealed AISI 52100 ball bearing steel through statistical analyses of variance (ANOVA). They have reported that Regression analyses have conducted to the development of simplified empirical models that can be effectively used to predict surface roughness and tool wear in end milling process. The present work proposes to investigate the effect of cutting parameters on the tool life and the level of vibrations on the machined part when dry face milling 52100 steel in annealed and hardened conditions using multi-layer coating micro-grain carbide inserts.

Analyses are carried out using the RSM method applied on a reduced TAGUCHI L9 experimental plan with corresponding milling cutting parameters, feed per tooth fz, the cutting speed Vc and the depth of cut ap.

## 2. Experimental procedure

### *2.1 Worked materials*

The worked material is a block (220×80×80 mm) AISI 52100 steel alloy the first block is annealed and the second block is quenched at 950°c temperature. The nominal chemical composition is referenced in Table1.

Table 2 shows the hardness obtained for each treatment.

### *2.2 Cutting tool*

Down milling operations have been performed using three multilayer coated carbides (TiN, TiCN, TiAlN) inserts R390 by [Sandvik Coromant ] have been investigated. Milling has been carried using a 25 mm mill cutter.

### *2.3 Machine tool*

Machining tests were realized on a vertical CNC milling Machine (EmcoMill E350) Speed range (50 – 10000 rpm), Spindle motor power 6.8 kW. Emco Win Nc Sinumerik 840D milling software (face milling cycle) is used.

Table 1 Chemical composition of AISI 52100 steel (in weight percent)

| C | Si | Mn | P | S | Cr | Ni | Mo | V |
|---|---|---|---|---|---|---|---|---|
| 0.95 | 0.35 | 0.4 | 0.03 | 0.025 | 1.50 | 0.1 | 0.1 | 0.05 |

Table 2 Rockwell hardness value

| Treatment type | Annealing | Quenching |
|---|---|---|
| Hardness (HRc) | 28 | 55 |

### *2.4 Measurement equipment*

#### *2.4.1 Microscopy measurement*

The optical microscope Motic is used to observe the tool wear evolution along the cutting tests. It permits to determine the tool life. The qualification criterion is the degradation of the tetragonal insertions. Classically, in industry, it is considered that acuity tool is degraded after a clearance wear of [Vb = 0.3 mm].

#### *2.4.2 Vibration measurements*

Specially designed for easy on site vibration measurement of all machinery, and predictive maintenance purposes. Wide frequency range (10 Hz~10 kHz) in acceleration mode. General Specifications: Sensor: Piezoelectric Accelerometer Measuring Range: Acceleration: 0.1~400 m/s²;

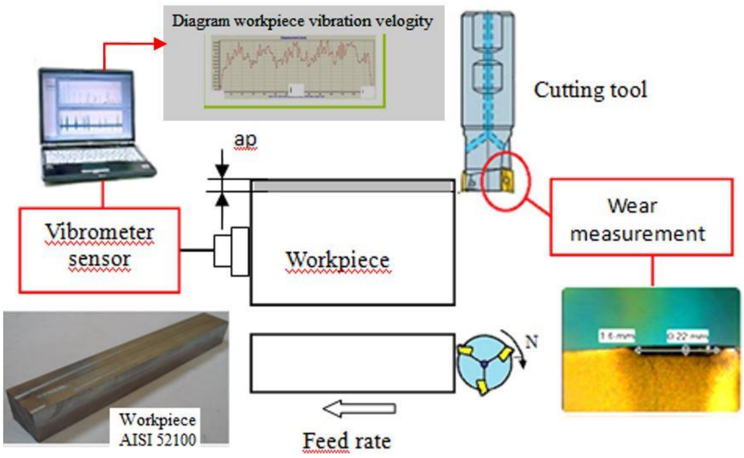



Fig. 1 Experimental setup

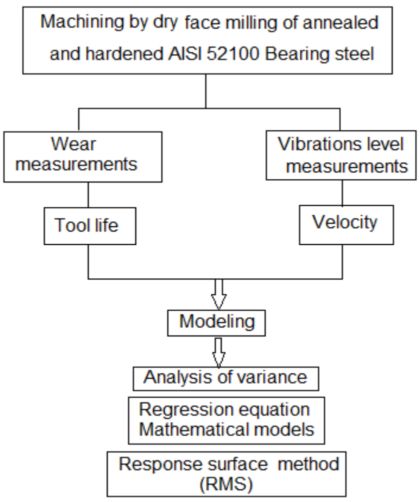



Fig. 2 Experimental procedure

Table 3 Factors and levels used in experimental plan

| Factors | Levels | | |
|---|---|---|---|
| Cutting speed Vc (m/min) | 60 | 100 | 140 |
| Feed per toth fz (mm/t) | 0.01 | 0.05 | 0.1 |
| Depth of cut ap (mm) | 0.5 | 1 | 1.5 |

Table 4 Taguchi L9 ($3^3$) reduced plan and experimental results

| | Vc (m/min) | fz (mm/t) | ap (mm) | Ta (min) | VBa (mm/s) | Th (min) | VBh (mm/s) |
|---|---|---|---|---|---|---|---|
| 1 | 60 | 0,01 | 0.5 | 290 | 0.48 | 116 | 0.72 |
| 2 | 60 | 0,05 | 1 | 255 | 0.32 | 85 | 2.40 |
| 3 | 60 | 0,1 | 1.5 | 240 | 1.82 | 64 | 3.52 |
| 4 | 100 | 0,01 | 1 | 190 | 0.45 | 54 | 4.23 |
| 5 | 100 | 0,05 | 1.5 | 140 | 1.55 | 45 | 6.35 |
| 6 | 100 | 0,1 | 0.5 | 160 | 0.83 | 62 | 4.13 |
| 7 | 140 | 0,01 | 1.5 | 90 | 2.35 | 40 | 9.16 |
| 8 | 140 | 0,05 | 0.5 | 105 | 0.93 | 45 | 7.35 |
| 9 | 140 | 0,1 | 1 | 85 | 1.95 | 40 | 8.16 |

0.3~1312 ft/s²; 0.0~40 g; Equivalent Peak, Velocity: 0.01~400 mm/s; True RMS, Displacement: 0.001~4.0 mm; Equivalent Peak-peak Frequency Range: Acceleration:10 Hz~1 kHz; Velocity: 10 Hz ~1 kHz, Displacement: 10 Hz~1 kHz. VBa and VBh are the average values of the spectrum recorded during the milling pass.

#### *2.4.3 Oven for heat treatment*

Thermolyne model 4800 benchtop muffle furnace, Thermo Scientific. Tmax = 1200°C with digital display is used for quenching parts.

Fig. 1 shows the experimental procedure adopted during the face milling tests.

The experimental procedure adopted is illustrated by Fig. 2.

## 3. Results and discussion

### *3.1 Microstructure observation*

Fig. 3(a) shows pearlite microstructure including some proeutectoid cementite at the prior austenite grain boundaries. homogeneous structure of black pearlite and white cementite mixture of relatively coarse cementite particles and ferrite. It is an austenitic structure with a medium hardness (28-30 HRC) it has a good machinability and good impact resistance.

Fig. 3(b) shows a martensitic structure in needles form and $Fe_3C$ of cementite reveals martensite, alloy carbides and some retained austenite. It is a very hard martensitic structure (50-65 HRC). It has a high resistance to friction but a difficult machinability and a fairly low impact resistance.

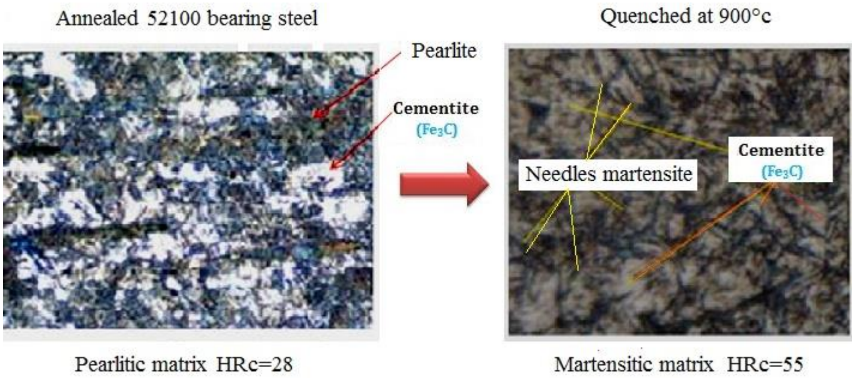



Fig. 3 Microstructure photography: (a) annealed steel; (b) Quenched steel

### 3.2 Flank wear evolution

During milling of annealed AISI 52100 steel with the conditions mentioned in Table 3, we observed that the flank wear on the auxiliary clearance face is greater and evolves more rapidly than the flank wear on the primary clearance face. (See Table 5 annealed steel, flank wear on auxiliary face). Tool life Ta given on the table 4 for annealed steel is obtained by following the evolution of flank wear in auxiliary clearance face. Allowable flank wear is [Vb = 0.30 mm].

### 3.3 Analysis of variance

In this investigation, the data processing based on response surface methodology are passed through the following steps:

Table 5 Flank wear photography obtained under following cutting conditions:
(Vc = 100 m / min, fz = 0.05 mm / t, ap = 1 mm)

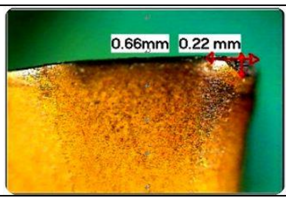
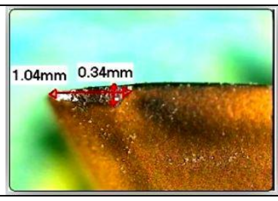
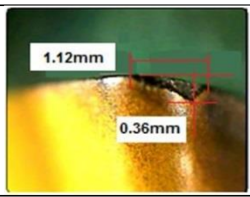
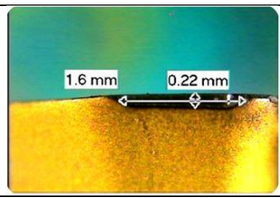
| **Annealed steel** | Flank wear on Primary clearance face | Flank wear on Aexiliary clearance face |
|---|---|---|
| Cutting condition<br>Vc = 100 m/min<br>fz = 0.05 mm/t<br>ap = 1 mm |  |  |
| **Hardened steel** | Flank wear on Primary clearance face | Flank wear on Aexiliary clearance face |
| Cutting condition<br>Vc = 100 m/min<br>fz = 0.05 mm/t<br>ap = 1 mm |  |  |

Table 6 ANOVA analysis for tool life Ta (Annealed steel)

| **Source** | DL | SCE | MCE | F-Value | P-Value | Contribution |
|---|---|---|---|---|---|---|
| **Model** | 6 | 45318,6 | 7553,1 | 39,04 | 0,025 | 99,15% |
| **Linear** | 3 | 22327,4 | 7442,5 | 38,46 | 0,025 | 98,13% |
| **Vc** | **1** | **18300,6** | **18300,6** | **94,58** | **0,010** | **93,00%** |
| **fz** | 1 | 251,6 | 251,6 | 1,30 | 0,372 | 2,50% |
| **ap** | 1 | 977,0 | 977,0 | 5,05 | 0,154 | 2,63% |
| **Interaction** | 3 | 467,8 | 155,9 | 0,81 | 0,595 | 1,02% |
| **Vc.ap** | 1 | 110,2 | 110,2 | 0,57 | 0,529 | 0,02% |
| **Vc.f** | 1 | 100,6 | 100,6 | 0,52 | 0,546 | 0,02% |
| **ap.fz** | 1 | 451,4 | 451,4 | 2,33 | 0,266 | 0,99% |
| **Erreur** | 2 | 387,0 | 193,5 | | | 0,85% |
| **Total** | 8 | | | | | 100,00% |

Table 7 ANOVA analysis for tool life Th (Hardened steel)

| **Source** | DL | SCE | MCE | F-Value | P-Value | Contribution |
|---|---|---|---|---|---|---|
| Model | 6 | 4951,57 | 825,26 | 16,18 | 0,059 | 97,98% |
| Linear | 3 | 2126,75 | 708,92 | 13,90 | 0,068 | 88,78% |
| **Vc** | **1** | **1023,93** | **1023,93** | **20,08** | **0,046** | **64,64%** |
| **fz** | **1** | **633,22** | **633,22** | **12,42** | **0,072** | **18,06%** |
| ap | 1 | 2,75 | 2,75 | 0,05 | 0,838 | 6,08% |
| Interaction | 3 | 464,80 | 154,93 | 3,04 | 0,257 | 9,20% |
| Vc.ap | 1 | 30,38 | 30,38 | 0,60 | 0,521 | 1,84% |
| Vc.f | 1 | 367,36 | 367,36 | 7,20 | 0,115 | 3,60% |
| ap.fz | 1 | 189,89 | 189,89 | 3,72 | 0,193 | 3,76% |
| Erreur | 2 | 101,99 | 50,99 | | | 2,02% |
| Total | 8 | | | | | 100,00% |

Table 8 ANOVA analysis for vibrations velocity VBa (Annealed steel)

| **Source** | DL | SCE | MCE | F-Value | P-Value | Contribution |
|---|---|---|---|---|---|---|
| Model | 6 | 4,40386 | 0,73398 | 28,48 | 0,034 | 98,84% |
| Linear | 3 | 3,47560 | 1,15853 | 44,96 | 0,022 | 78,13% |
| **Vc** | **1** | **1,72887** | **1,72887** | **67,09** | **0,015** | **45.30%** |
| **fz** | **1** | **0,36300** | **0,36300** | **14,09** | **0,064** | **7.35%** |
| **ap** | **1** | **1,11673** | **1,11673** | **43,33** | **0,022** | **25.48%** |
| Interaction | 3 | 0,92271 | 0,30757 | 11,94 | 0,078 | 20,71% |
| Vc.ap | 1 | 0,43961 | 0,43961 | 17,06 | 0,054 | 0,01% |
| Vc.f | 1 | 0,83884 | 0,83884 | 32,55 | 0,029 | 6,18% |
| **ap.fz** | **1** | **0,64684** | **0,64684** | **25,10** | **0,038** | **14,52%** |
| Erreur | 2 | 0,05154 | 0,02577 | | | 1,16% |
| Total | 8 | | | | | 100,00% |

Table 9 ANOVA analysis for vibrations velocity VBh (hardened steel)

| **Source** | DL | SCE | MCE | F-Value | P-Value | Contribution |
|---|---|---|---|---|---|---|
| Model | 6 | 62,4526 | 10,4088 | 30,32 | 0,032 | 98,91% |
| Linear | 3 | 39,1349 | 13,0450 | 38,00 | 0,026 | 98,81% |
| **Vc** | **1** | **29,0461** | **29,0461** | **84,61** | **0,012** | **85,81%** |
| fz | 1 | 3,5499 | 3,5499 | 10,34 | 0,085 | 12,31% |
| ap | 1 | 0,2188 | 0,2188 | 0,64 | 0,508 | 0,69% |
| Interaction | 3 | 0,0644 | 0,0215 | 0,06 | 0,975 | 0,10% |
| Vc.ap | 1 | 0,0424 | 0,0424 | 0,12 | 0,759 | 0,09% |
| Vc.f | 1 | 0,0003 | 0,0003 | 0,00 | 0,981 | 0,00% |
| ap.f | 1 | 0,0043 | 0,0043 | 0,01 | 0,921 | 0,01% |
| Erreur | 2 | 0,6866 | 0,3433 | | | 1,09% |
| Total | 8 | | | | | 100,00% |

Set a Taguchi plan L9, start the analysis of variance of tool life and vibration measurement. To define the mathematical models and the graphical representations of the effects for each input parameters on the outputs.

Tables 6 to 9 show the analysis of the variance for tool life and vibration levels.

In Table 6 the analysis show that the cutting speed (Vc) is the most significant parameter on tool life in annealed AISI 52100 steel case. The percentage of contribution is 93.00%, the other parameters and the interactions have a small contribution.

Table 7 shows the results of tool life analysis for hardened steel, it can be noted that the cutting speed is also the most significant parameter on the tool life. the contribution percentage is 64.64% for (Vc) the contribution of feed per tooth(fz) exceeds 18.06%, for depth of cut (ap) and interactions, their contributions are also very low. The ANOVA for vibrations velocity measurement during milling of AISI 52100 steel in annealed state are given in Table 8, cutting speed, depth of cut and feed per tooth are the most significant parameters with (45.30%, 25.48% and 7.35%) contribution. The interaction (ap×fz) have a 14.52% of contribution. Other interactions have a negligible effect.

The analysis of vibration velocity results during milling of AISI 52100 steel in hardened condition are shown in Table 9, cutting speed (Vc) has the most significant effect on the generation of vibrations, with 85.81% contribution, the feed per tooth is the second parameter with 12.31% contribution. The depth of cut and the interactions always remain with insignificant effects.

### *3.4 Mathematical modeling*

Regression is a technique for studying the functional relationship between variables decision of process. This technique can be useful for manufacturing description data process, estimation and control of parameters (Choudhury and El-Baradie 1998, Cakir *et al*. 2009, Selaimia *et al*. 2017). Mathematical models are established to predict the approximate values of tool life and vibrations directly from the model.

The models are as follows:

Tool life model for annealing steel see Eq. (1)

$$\boldsymbol{Ta} = 472{,}901 - 2{,}106Vc - 530{,}534fz - 124{,}852ap - 4{,}655Vc \times fz + 0{,}463Vc \times ap + 788{,}90fz \times ap \quad (1)$$

Coefficient of determination (**$R^2$ = 0.991**)
Vibrations levels model for annealing steel see Eq. (2)

$$\boldsymbol{Vba} = 1{,}924 - 0{,}005 \times Vc + 14{,}712fz - 5{,}011ap - 0{,}307Vc \times fz + 0{,}040Vc \times ap + 29{,}864fz \times ap \quad (2)$$

Coefficient of determination (**$R^2$ = 0,988**)
Tool life model for hardened steel, see Eq. (3)

$$\boldsymbol{Th} = 231{,}946 - 1{,}154Vc - 234{,}177fz - 141{,}050ap - 2{,}558Vc \times fz + 0{,}846Vc \times ap + 511{,}691fz \times \mathrm{ap} \quad (3)$$

Coefficient of determination (**$R^2$ = 0,979**)
Vibrations levels model for hardened steel see Eq. (4)

$$\boldsymbol{Vbh} = -5{,}211 + 0{,}080Vc + 13{,}231fz + 1{,}910ap - 0{,}095Vc \times fz + 0{,}0007Vc \times ap + 2{,}436fz \times ap \quad (4)$$

Coefficient of determination (**$R^2$ = 0,989**)

The coefficients of determination are greater than 96%, we can say that these models are applicable to predict the responses for given parameters.

### *3.5 Surface method analysis*

#### *3.5.1 Tool life response*

Fig. 4 shows the evolution of tool life according to cutting parameters (Vc, and fz), Fig. 4(a) represents surface analysis for annealed steel state and (Fig. 4(b)) for hardened steel state. It shows that any increase of cutting speed results a sharp decrease in tool life, for same conditions, life of inserts with mild steel (annealed) becomes longer. With annealed steel, due to the difficulty of penetration and impact between the workpiece, tool life which increases in hard machining. increasing the depth of cut has no significant effect on tool life in both cases. Fig. 4(b) shows that for hardened steel the increasing feed per tooth also contributes to decreasing the tool life Th.

#### *3.5.2 Vibrations velocity*

Fig. 5 shows the effect of cutting speed and feed per tooth on the vibrations generated during

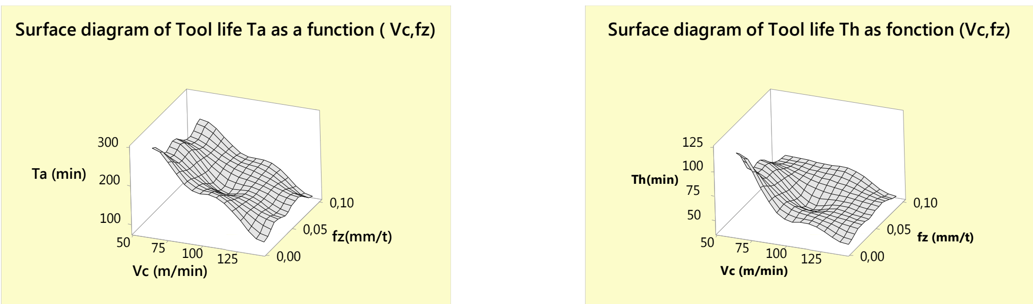



Fig. 4 Surface diagram of tool life Ta and Th versus cutting conditions

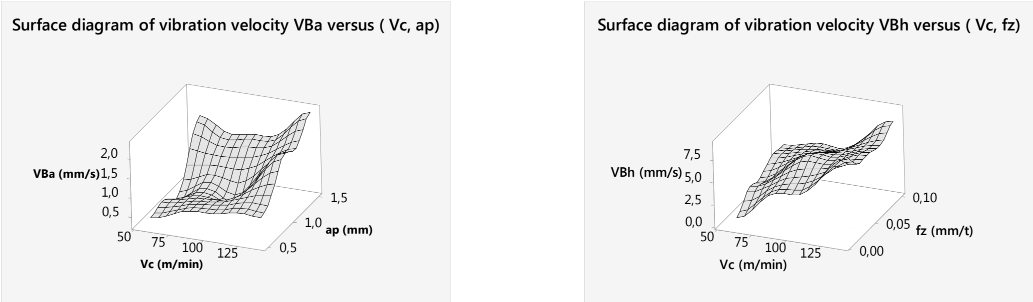



Fig. 5 Surface diagram of Vibration velocity VBa and VBh versus cutting conditions

milling. In Fig. 5(a) and for annealed steel, the increase cutting speed and depth of cut causes the increase in the level of vibrations. In Fig. 5(b) and for hardened steel, the effect of depth of cut and feed per tooth is greater. Increasing cutting speed increases vibrations level. The vibrations can reach 7.3 m/s for the hard steel which implies the instability of the system which directly influences on the state of surface and decrease the tool life duration.

Table 10 Optimal response values

| Responses | Vc | fz | ap | Adjusted value | Composite desirability |
|---|---|---|---|---|---|
| ***Ta***(*min*) | 60 | 0,01 | 0,5 | 291,111 | 1 |
| ***Th***(*min*) | 60 | 0,01 | 0,5 | 110,222 | 0,923977 |
| ***VBa***(*mm/s*) | 76,16 | 0,041 | 0,651 | 0,0666 | 1 |
| ***VBh***(*mm/s*) | 60 | 0,01 | 0,5 | 0,756667 | 0,995656 |

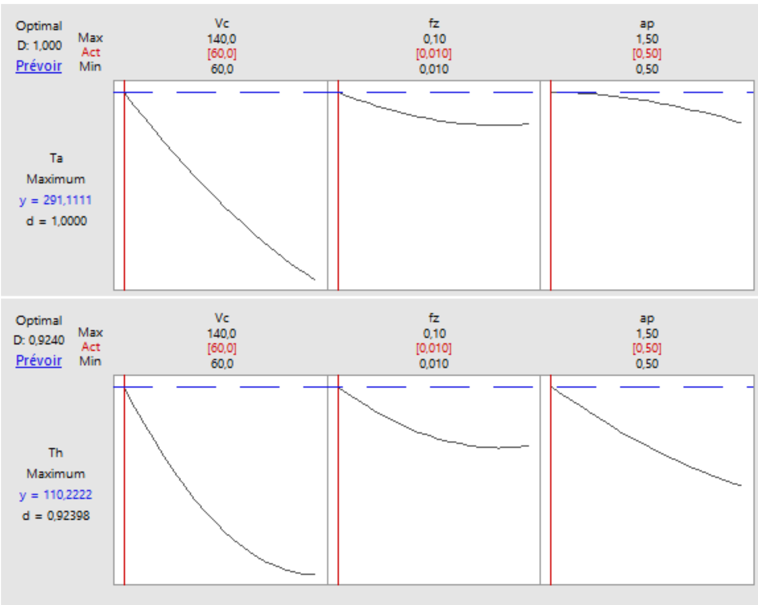



Fig. 6 Optimization diagram for Ta and Th

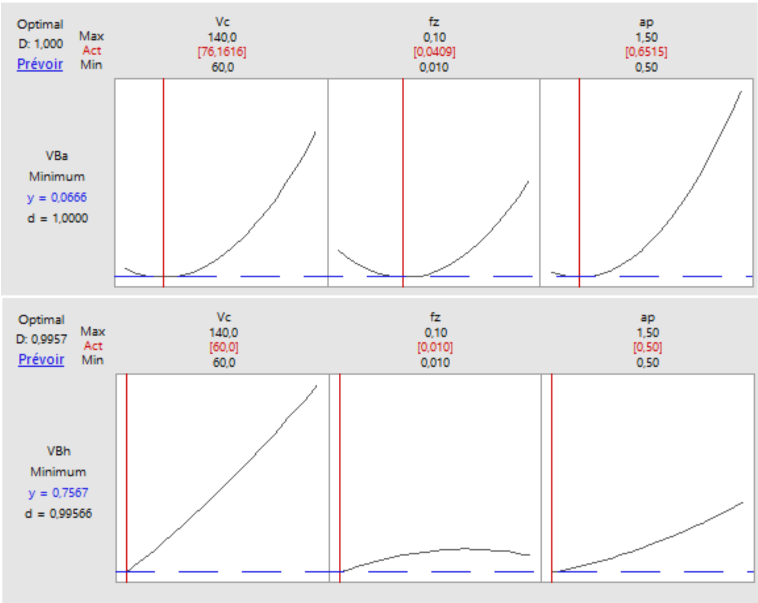



Fig. 7 Optimization diagram for VBa and VBh

### *3.6 Optimization of responses*

Table 10 presented the optimal responses of tool life and level velocity according the constraint maximum for (Ta,Th) and minimum for (VBa,VBh)

Figs. 6 and 7 show the optimization diagrams for all responses. To maximize tool life Ta and Th, it is necessary to machine the annealed or treated steel with the cutting conditions (Vc = 60 m/min, fz = 0.01 mm / t and ap = 0.5 mm). Increasing the cutting conditions leads to a decrease milling tool life. To minimize the level of vibrations VBa and VBh, the values of the cutting parameters must be reduced. For industrial application, the face milling parameters are chosen according to the constraints (Maximum tool life, minimum Vibration velocity).

## 4. Conclusions

This experimental research on the face milling of AISI 52100 annealed and hardened steel given the following conclusions:

- The machining of annealed steel AISI 52100 is easier than when it is hardened, tool life obtained during face milling of annealed steel is approximately two and a half times greater than the duration tool life during milling of hardened steel (Ta = 2.5 Th).
- Multilayer Coated inserts (R390 TiN, TiCN, TiAlN) by [Sandvik coromant] can give larger tool life Ta. These insert can be recommended for industrial applications
- Cutting speed is the most important factor affecting the tool life of the milling inserts. This is checked for the two states of steel (annealed and quenched)
- For velocity vibrations, in the case of annealed steel, the depth of cut affects vibrations more

than the cutting speed and the feed rate. On the other hand, in the case of hardened steel, the cutting speed is the most influential parameter.

- Increasing the hardness of the part decreases the tool life and increases the level of vibrations generated during milling.
- The established mathematical models allow to predict the response. The graphical representation of the outputs facilitates the interpretation of the results and clearly illustrates the effect of the input factors on the responses.

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*CC*

## Nomenclature

| | |
|---|---|
| *Vc* | Cutting speed (m/min) |
| *fz* | Feed per tooth (mm/t) |
| *ap* | Axial depth of cut (mm) |
| *ae* | Radial depth of cut (mm) |
| *T* | Tool life (min) |
| *Ta* | Tool life (min) for annealed steel |
| *Th* | Tool life (min) for hardened steel |
| *VB* | Vibrations velocity (mm/s) |
| *VBa* | Vibrations velocity (mm/s) for annealed steel |
| *VBh* | Vibrations velocity (mm/s) for hardened steel |
| *HRC* | hardness value by Rockwell |
| Ra | Arithmetic Surface roughness (µm) |
| *Rt* | Total Surface roughness (µm) |
| *Rz* | Average surface roughness (µm) |
| TiN | Titanium nitride |
| TiCN | Titanium carbonitride |
| TiAlN | Titanium nitride alumina |

## Abbreviations

| | |
|---|---|
| *RSM* | Response surface methodology |
| *PVD* | Physical vapour deposed |
| *CVD* | Chemical vapour deposed |
| *CNC* | Computer numerical control |
| *AISI* | American Iron and Steel Institute |
| *ANOVA* | Analysis of variance |
| *MS* | Mean of squares |
| *P%* | Percentage of contribution |
| *df* | Degree of freedom |
| *SS* | Sum of squares |
| *S/N* | Ratio signal-to-noise ratio |
| *AISI* | American Iron and Steel Institute |