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Research Article

Investigation of Nitriding Effect on Cutting Vibration of Indexable End Mill During the Straight Groove

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ABSTRACT

End-milling is a cutting technology that removes material from machined workpieces by end mill and is widely used to manufacture parts. Also, nitriding is a surface hardening process with a lot of effects on mechanical properties like damping ratio. This study investigated the effect of gas nitriding on a nitrided end mill in comparison with an unnitrided end mill and showed a 22 and 23 percent decrease on average in peak values and Root Mean Square values respectively. This improvement can be a result of increasing damping ratio or stiffness or two parameters simultaneously. In the next step, Modal analysis was carried out on two nitrided and unnitrided samples, and the damping ratio and natural frequency were measured by constant young modulus and showed a 14 percent increase in damping ratio without any significant change in natural frequency. Moreover, by modeling and analyzing the 3D model of indexable end mills It was verified that nitriding can have a 3 percent effect on increasing natural frequency at maximum. As a result, It concluded that the reported vibrational improvement of nitrided indexable end mill was due to improving damping ratio of steel not increasing natural frequency. In this regard, nitrided indexable end mills lead to improvement in machining efficiency, reducing energy consumption, manufacture of high-quality parts and it will ultimately reduce costs.

1. Introduction

Production lines are eagerly seeking to incorporate new scientific properties into their products to stand out from competitors, with nitriding considered as a key solution. Nitriding is described as a thermochemical surface treatment in which nitrogen is diffused from an ammonia atmosphere into steel below eutectoid temperature [1]. Due to the low solubility of nitrogen in ferrite, the nitrides precipitate during the nitriding process [2]. This precipitation creates a compound layer and an underlying diffusion zone near the surface of the steel after nitriding. This compound layer also known as the white layer consists of nitrides and can improve mechanical properties [3]. Beregovenko et al. [4] investigated the effect of nitriding on steel Ck 45 under different nitriding conditions and demonstrated that damping of Ck45 can be improved up to six times in the best nitriding parameter combination.

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Therefore, nitrided tools can have better vibration conditions in comparison to conventional tools. Tomonori et al. [5] studied on mechanical properties and corrosion resistance of nitrided austenite stainless steel and showed significant improvement on it. They demonstrated that yield stress almost remained identical to the previous level while ultimate strength increased up to a maximum level after nitriding and pitting resistance improved. Hung et al. [6] investigated SACM 645 Steel specimens with different substrate hardness under gas nitriding and showed a significant increase in wear resistance for the nitrided specimens. They also improved the fatigue limit by 44 percent by 96 hours of gas nitriding. Valdes et al. [7] studied contact fatigue behavior of nitrided AISI 316L steels and the results showed that the thinnest thickness of the nitrided layer exhibits better resistance to standing contact fatigue.

The machining industries are facing a great challenge to achieve high quality, good surface finish, and high material removal rate to economizing in machining [8]. Tool vibration is one of the key factors in increasing surface quality and productivity so a lot of efforts have been made to control and reduce tool vibration in the machining industry [9], [10]. Bashir et al. [11] used the variable pitch method to reduce end mill vibration in end milling and demonstrated that forced vibration was reduced during milling by variable pitch end mill in comparison to equal pitch milling tool. Dombovari et al. [12] investigated the effect of helix angle variation on milling stability and showed that cutting can be done extremely in high depth at high spindle speeds by this method. Hayati and Madoliat [13] proposed an endmill with a core damper fitted inside and used a frictionally damped mechanism to reduce vibration. They showed that because the boundary between the core damper and the body is not separable, the deflection of the tool is hindered by the core damper so this causes a high improvement in tool performance. Shibata et al. [14] investigated the effect of gas nitriding on fatigue behavior of titanium alloy and showed premature fatigue crack initiation in nitrided materials and also a significant decrease in crack resistance in fatigue behavior. Yang et al. [15] used two degrees of freedom tuned mass damper to damp the first mode of vibration in the milling process and finally demonstrated that the amplitude of the first mode of vibration reduces up to 80 percent and critical depth of cut doubles by using this method and finally reached good accordance between theoretical and experimental results. Mahdikhani et al. [16] studied the effect of the variable pitch in indexable cutting tool on AISI 4140 steel surface finish in milling and showed using the variable pitch method decrease the vibration of the tool by about 50 percent and surface finish improvement more than 200 percent. Fallah et al. [17] employed a novel adaptive control system to suppress cutting tool vibration and enhance its dynamic stiffness, enabling higher depths of cut during internal turning.

It should be noted that the addressed studies indicate that vibration control methods around tool vibration can be generally categorized into two groups. The first group focuses on enhancing the mechanical properties of materials, while the second group involves the use of dampers to control vibrations. It is important to note that the effect of nitriding on cutting tools has not yet been studied and existing researches on nitriding is limited to examining steel properties before and after the operation, rather than its application to cutting tools and this is the focus of this study.

This study investigated the effect of gas nitriding on the indexable end mills to show how the nitriding affected the end milling process. For this purpose, two nitrided and unnitrided tools were used on CNC machines, and vibration during machining was monitored, revealing a significant decrease in tool peaks and Root Mean Square (RMS) amplitude of vibration. To interpret this improvement, a modal test was conducted to examine the effect of nitriding on the damping ratio and natural frequency. The results showed increasing damping ratio without a change in natural frequency. It was concluded that nitriding affected the damping ratio without having a significant impact on tool rigidity, a claim that was verified through modeling and calculation of the natural frequency for nitrided and unnitrided tools, with the nitrided layer applied to one of the end mills. The theoretical analysis demonstrated that the nitriding layer could increase the natural frequency by up to 3 percent, indicating that the natural frequency remained largely unchanged. Therefore, nitriding enhanced the damping ratio of the nitrided indexable tool without any significant change in natural frequency, suggesting that this method could be an effective approach for reducing vibration during end milling.

2. Experimental Conditions

To investigate the effect of gas nitriding on the end-milling process, two commonly used indexable endmills shown in Fig. 1. were used. The effect of nitriding on tool vibration during machining was compared by machining two straight grooves, as shown in Fig. 2. In both cases, the same conditions in terms of run out and overhang were maintained, and the used material was steel 1.7225 also known as MO40 steel and AISI 4140.

Fig. 1. Indexable Endmill used in machining straight groove.

Fig. 2. shows the test setup and shows the coordinate system of end milling. End milling of straight grooves was conducted on a LEADWELL CNC milling machine (made by LEADWELL CNC MACHINES MFG.CORP., Taichung City, Taiwan).

The cutting tool was an indexable end-mill with APKT 10 inserts and cutting diameter 20 millimeters, shank diameter 20 millimeters, and total length of 150 millimeters made by the Iranian X-Hold Company. As shown in Fig. 1. the tool holder has three APKT inserts made by the Chinese Hard-stone Company. The configuration also had a 90 mm stick-out length for the tool holder with a 0.05 mm run-out in the setup. According to Fig. 2. the AC-102-1A sensors were mounted rigidly on the spindle of the milling machine and the workpiece was fixed onto the clamp.

CTS acceleration sensor was used to monitor the dynamic response of end milling operation by a DEWE-43 data collector, where the sensor sensitivity was 100 mv/g and the frequency range was 1–10KHz. The acquired vibration signal was also entered into the computer for further analysis and the sampling frequency was 20000 Hz.

To have a better understanding of signal analysis, the coordinate system of end-milling is shown in Fig. 3. where X, Y, and Z directions correspond, respectively to the feed direction, perpendicular direction, and the axis of the end mill. The coordinate system is located in the intersection point of the tool axis and the machined surface.

The CNC was run at 1000 RPM and 600 mm/min with 1 mm depth of cut and a 90 mm overhang twice for nitrided tool and unnitrided tool to examine how nitriding affected the RMS of vibration in feed, perpendicular and axial directions. The results showed a significant decrease in vibration peaks and RMS for the nitrided tool.

By lowering vibration peaks and RMS amplitude during the process, better surface quality, reduced tool wear, increased machining accuracy, and enhanced productivity can be achieved. Therefore, this is of significant importance.

A modal test was conducted to measure changes in damping ratio and natural frequency after nitriding. It should be noted that the quench and temper, as well as the nitriding conditions, for both the modal test samples and milling tools, were consistent with the previously established conditions.

Fig. 4. shows two identical samples made from steel 1.7225 by the composition analysis shown in Table 1. both of them quenched and tempered, and only one of them nitrided.

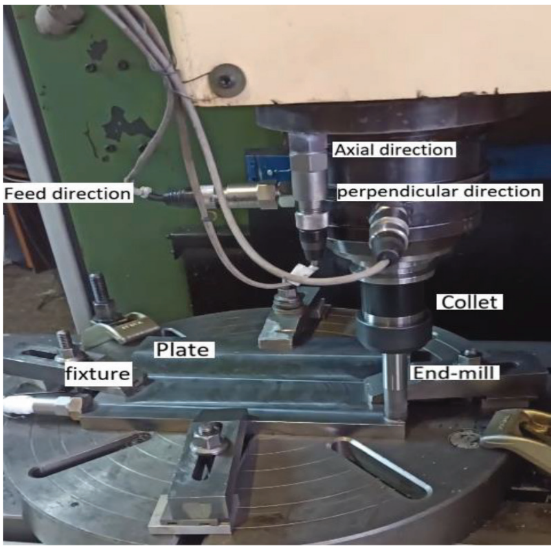

Fig. 2. Test setup.

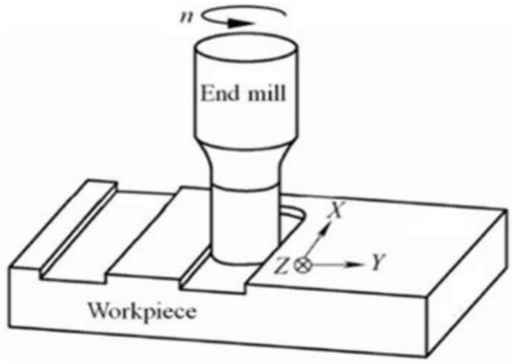

Fig. 3. Detailed milling coordinate system. X, Y, and Z direction correspond to feed, perpendicular and axial, respectively.

The samples were heat-treated to harden the core by heating up to 860 degrees and keeping it at this temperature for 45 minutes. The process was followed by quenching in agitated 54-degree mineral oil and was washed in hot water and tempered in the air at 275 degrees.

As shown in Fig. 5. the samples were hung on the provided structure, and the modal test was carried out to determine the natural frequency and damping ratio for the samples before and after the nitriding process.

It should be noted that the test was conducted in the thin (6 mm) direction with different impact locations and sensor installation locations, because this direction had a higher ratio of nitrided depth to the overall depth.

The modal test was carried out with different sensor installation locations, and the acceleration frequency spectrum diagram were extracted for each case, as shown in Fig. 6. and Fig. 7. The resultant natural frequencies and damping ratios are shown in Table 2.

3. Results and Discussion

3.1. Waveform Characteristic of Cutting Vibration During the Straight Groove

Fig. 9. and Fig. 10. show the time domain of the vibration measured during end milling of the straight groove for nitrided and unnitrided indexable end mills which include instantaneous values of acceleration as a function of time. Both waveforms describe cutting operation a few seconds before engagement until a few seconds after engagement.

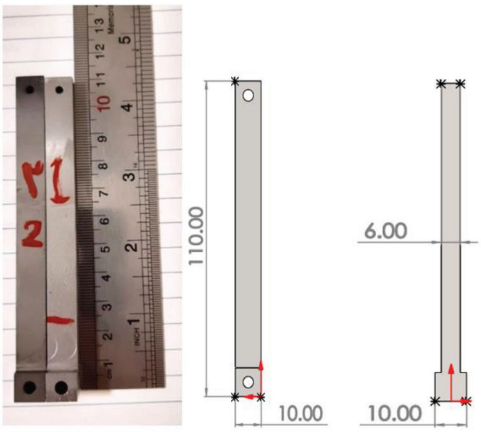

Fig. 4. The dimension of the samples used in the experiment.

Table 1. Analysis of used steel in the experiments.

42CrMo4/1.7225	C	Mn	Si	P	S	Cr	Mo
	0.398	0.85	0.33	0.016	0.003	0.90	0.160

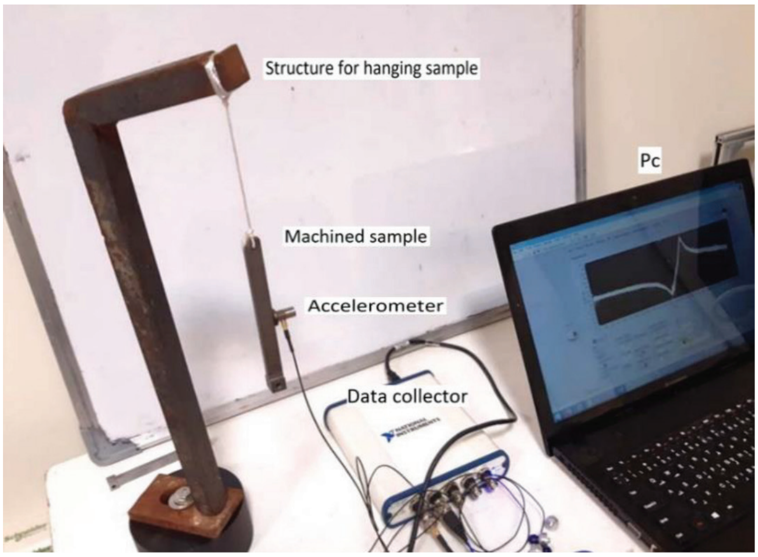

Fig. 5. Modal test on the nitrided piece and unnitrided piece.

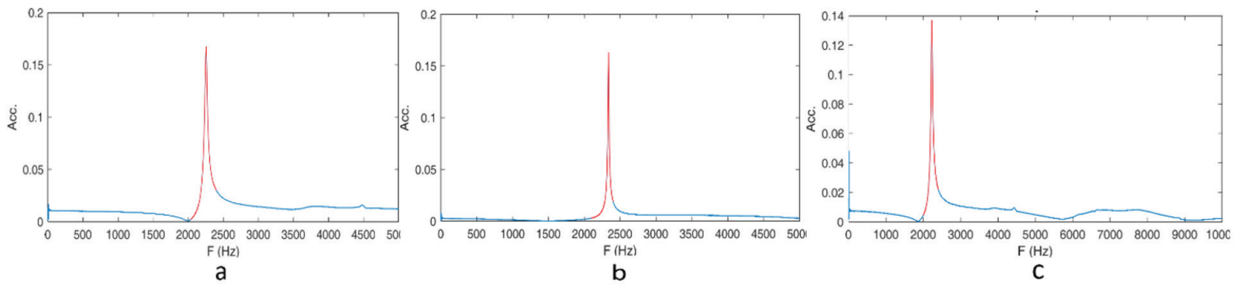

Fig. 6. Acceleration frequency spectrum diagram for unnitrided sample. a, b and c correspond to the top, down, and center respectively.

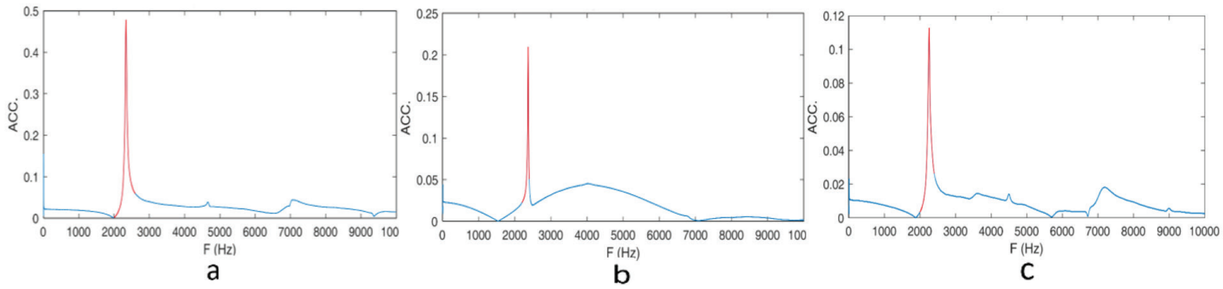

Fig. 7. Acceleration frequency spectrum diagram for nitrided sample. a, b and c correspond to the top, down, and center respectively.

Table 2. Results of the modal test in the thin direction.

Number	impact location	sensor installation location	unnitrided sample		nitrided sample	
			Natural Frequency (Hz)	Damping ratio	Natural Frequency (Hz)	Damping ratio
1	top	top	2254	0.007	2339	0.008
2	down	down	2336	0.003	2368	0.003
3	center	center	2226	0.008	2254	0.010

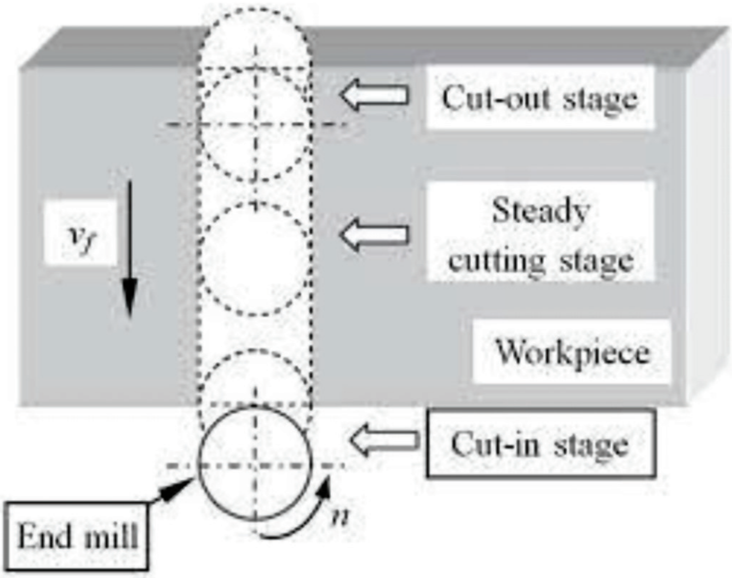

Fig. 8. Three stages of end milling straight groove.

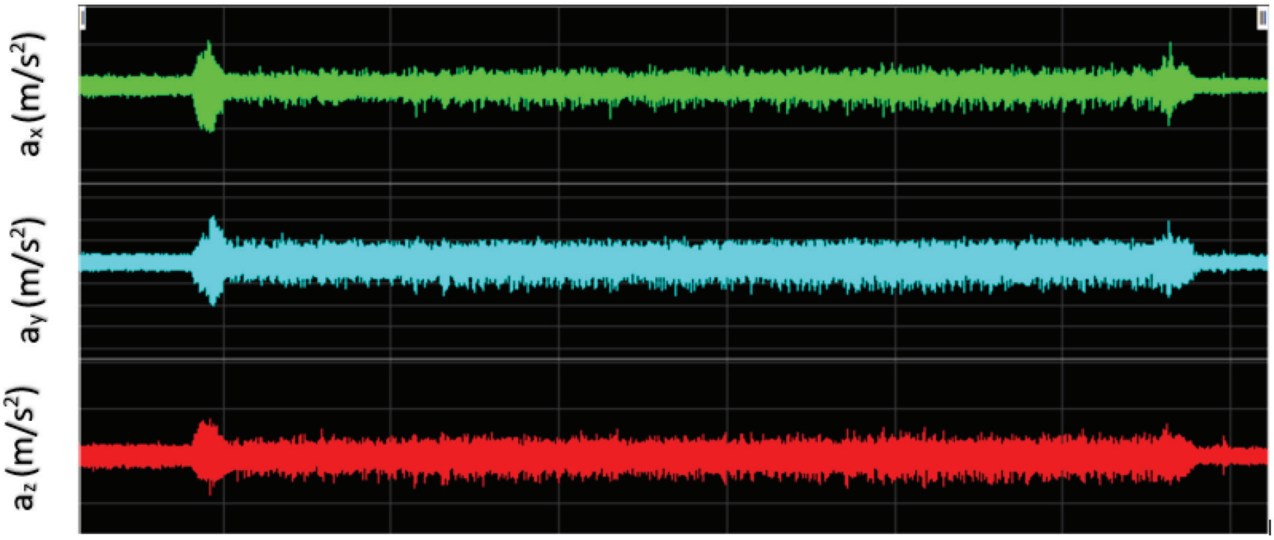

Fig. 9. Time-domain waveform of the cutting vibration of unnitrided indexable end mill.

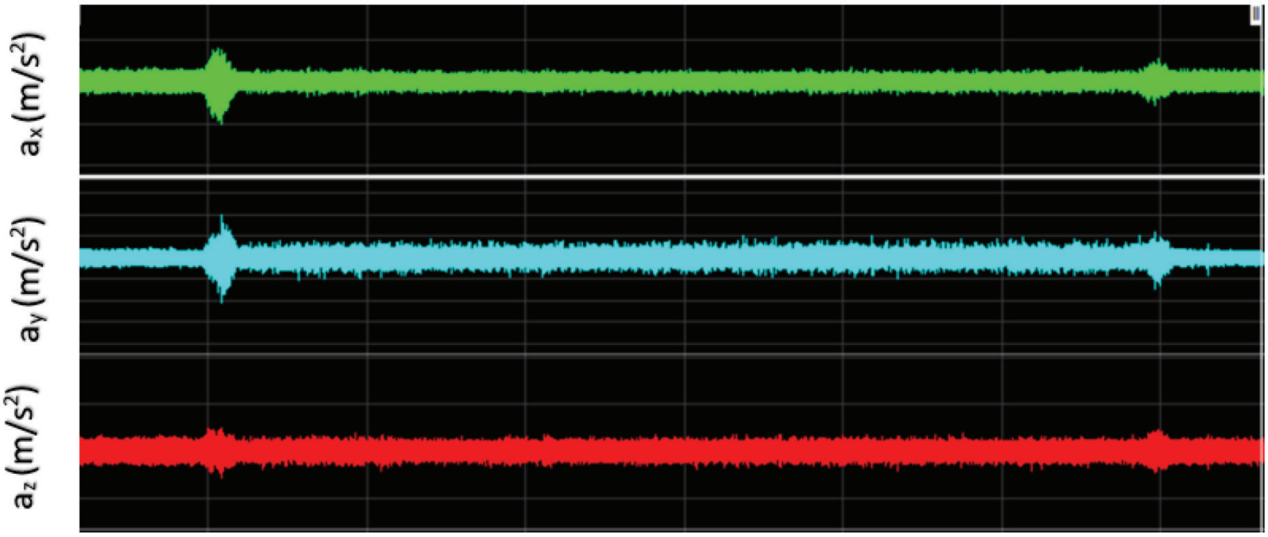

Fig. 10. Time-domain waveform of the cutting vibration of nitrided indexable end mill.

By considering the waveform and the process of cutting, it is clear that the waveform can be divided into three sections marked as A, B, and C which corresponds to the three stages of the milling namely as cut-in, steady-state cutting, and cut-out. Both mentioned waveforms Show that between each stage there is a peak value of acceleration vibration of dynamic interaction between the end mill and the workpiece and during the steady cut, it has a lower peak value for acceleration.

From the time-domain waveform, various acceleration variables, such as the mean value, Peak value and the root mean square (RMS), etc can be extracted. According to Fig. 9. and Fig. 10. the peak acceleration value along the X, Y, and the Z directions within the steady cutting process for nitrided and unnitrided indexable end-mill are, respectively 3.85, 4.20, and 1.75 for unnitrided piece, and 3.10, 3.40, 1.35 for the nitrided piece which shows that, during end-milling of the straight groove, the acceleration peaks along with the three directions decreased 22 percent on the average and the components of the vibration from largest to smallest are in turn the perpendicular, feed, and axial direction.

By calculating average RMS both for nitrided and unnitrided end mill in the steady-state stage, the results summarized in Table 3. and the results imply a significant 23 percent decrease on average.

3.2. Nitriding Effect on The Natural Frequency

Microhardness measurements, as shown in Fig. 11.

were used to determine the hardness distribution from the surface layer to the bulk. The first 20 µm of the surface was identified as the white layer, and measurements commenced at a depth of 50 µm from the edge, with increments of 100 µm. It should be noted that the nitriding process was conducted at 500°C for 12 hours, with a substrate hardness of 31 HRC.

Based on the CNS 14288-G2272 standard [18], the effective depth of the nitrided specimen was calculated as the hardness value reaches the substrate hardness plus 50 HV. Consequently, the effective depth in the sample was determined to be 300 µm. During nitriding operation, the nitrogen concentration starts from the maximum amount in the surface and decreases to the depth of cut, and Valdes [7] researches also demonstrate this behavior. For simplicity, we overestimated a constant young modulus of 300 GPa for the effective nitrided layer and modeled the nitrided and unnitrided steel to investigate the effect of the nitrided layer on the natural frequency of the end mill.

As shown in Fig. 12. and Fig. 13. the end mill used for machining a straight groove was modeled and meshed with a 1 mm mesh size. Modal analysis was conducted for both the nitrided end mill and the unnitrided end mill, incorporating a 0.3 mm hardened layer in the nitrided. the boundary condition for contact point with collect was assigned as a fixed boundary. The results for unnitrided and nitrided end mill are respectively 1540 and 1580 Hz which shows only 3 percent improvement which is ignorable.

By considering the FFT of these two end mills during experimental straight groove in Figure 14 it is obvious that the natural frequency for both end mills didn't change so much. Hence, it can be concluded that the improvement in vibration peak and RMS of the nitrided indexable end mill is due to the increased damping ratio of the steel not improving tool rigidity.

Table 3. Comparison between average RMS between nitrided and unnitrided tools during steady-state.

Direction	**Unnitrided $\frac{m}{s^2}$**	**Nitrided $\frac{m}{s^2}$**	**Improvement (%)**
Feed	3.6	2.9	19.4
Axial	1.7	1.2	29.4
Vertical	4	3.2	20

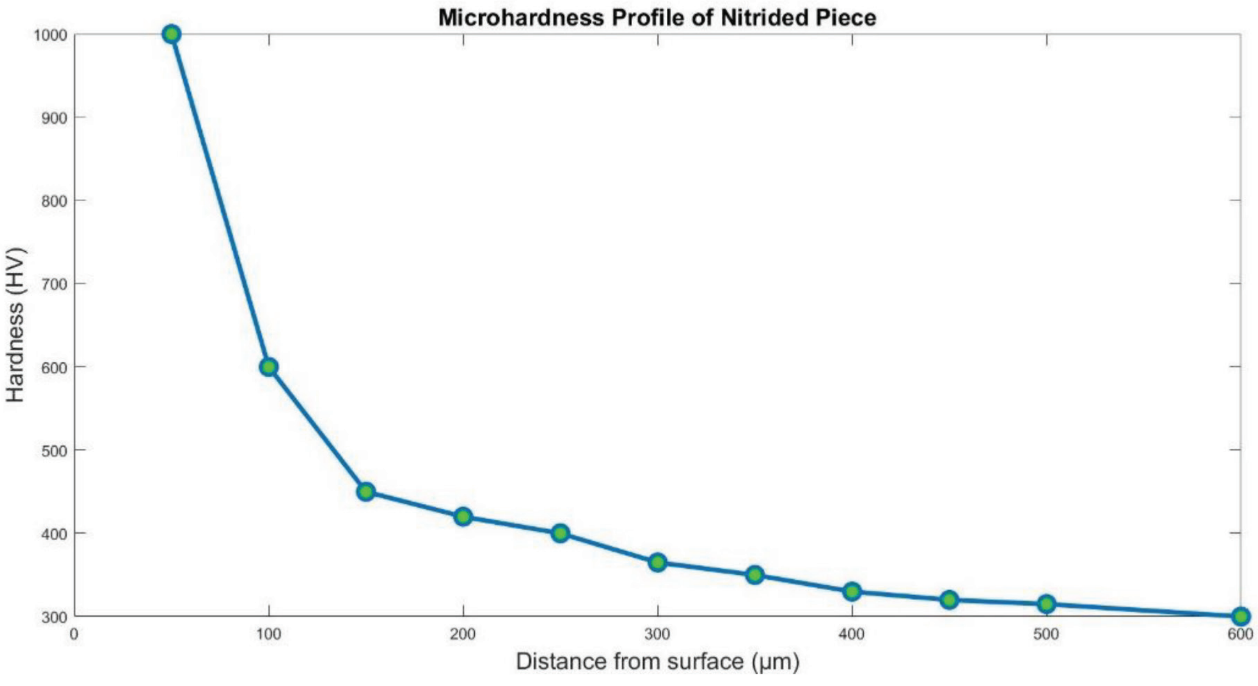

Fig. 11. Microhardness profile of nitrided specimen nitrided at given condition.

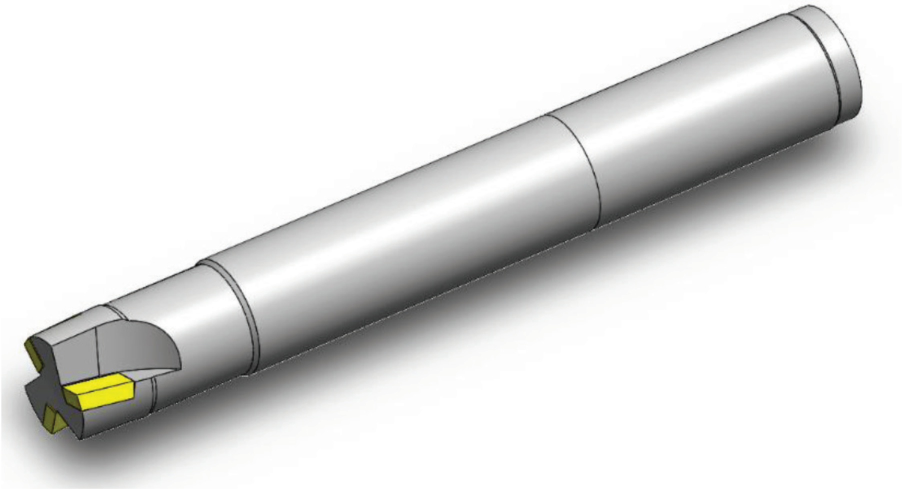

Fig. 12. 3D model of the used end mill in straight groove operation.

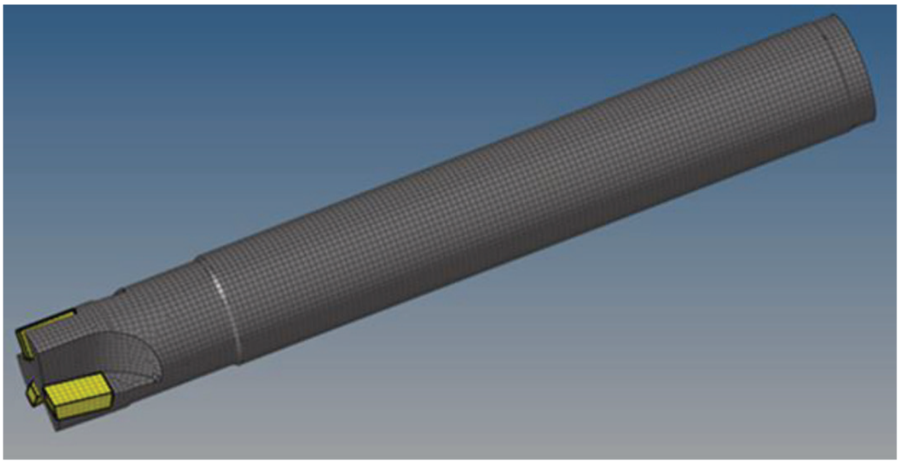

Fig. 13. Meshing used end mill by 1 mm mesh size.

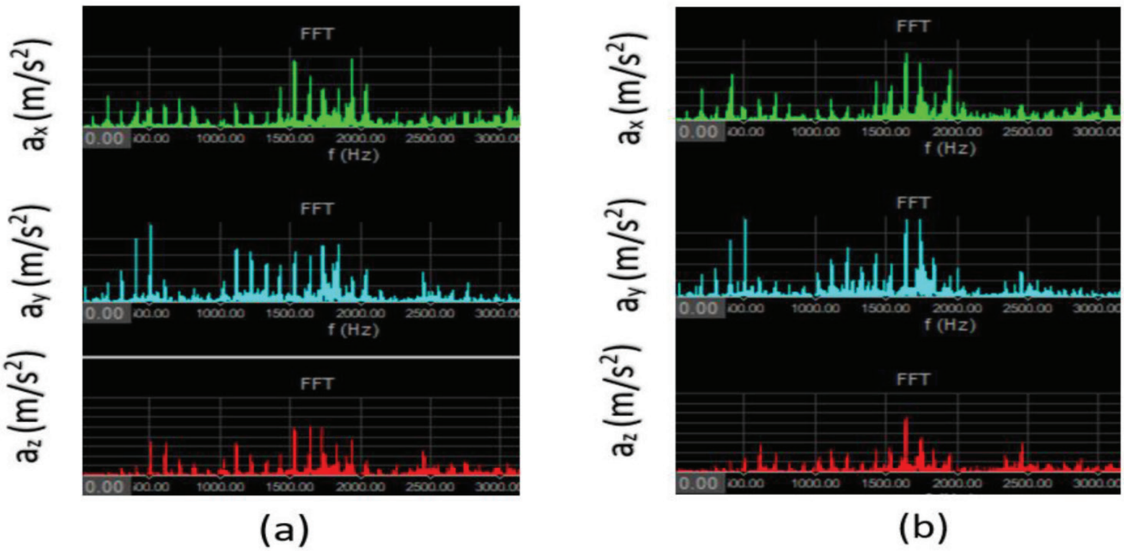

Fig. 14. FFT of vibration waveform during end milling for- a) unnitrided- b) nitrided end mill.

4. Conclusions

The depth of the nitrided layer was 600 µm and the hardness dropped sharply from 1000 HV to 300 HV.

This study has demonstrated the significant impact of gas nitriding on the performance of indexable end mills, particularly in reducing vibration during machining operations. Through experimental investigations and modal analysis, it was observed that nitriding reduced vibration peaks and RMS values by 22% and 23%, respectively, during the steady cutting condition. This improvement was attributed to an increase in the damping ratio of the nitrided tools, while the natural frequency remained largely unchanged, as confirmed by theoretical modeling and experimental analysis.

The microhardness profile showed an effective nitrided layer depth of 300 µm, further emphasizing the structural enhancements due to the nitriding process. However, only a marginal 3% increase in natural frequency was observed, indicating that tool rigidity remained unaffected.

It should be noted by enhancing the damping properties of the end mill, nitriding improved machining efficiency, resulting in better surface quality, reduced tool wear, and increased productivity. These findings highlight the practical benefits of applying nitriding as a surface treatment for machining tools, offering an economical approach to achieving superior performance and cost efficiency in manufacturing processes.

5. Declarations Section

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Conflicts of interests the authors declare that they have no conflicts of interests.

Availability of data and material the authors of this publication confirm that the data supporting the funding of this study are available as it's supplementary material.

Availability of data and material Authors of this publication confirm that the data supporting the findings of this study are available as Its supplementary materials.

Code availability Not applicable

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Consent to participate Not applicable

Consent for publication the present paper does not require any consent to publish since all the figures, tables, and text are original.

Authors' contributions M.H. and E.I.: resources; M.H. and E.I.: investigation; M.H. and E.I.: data curation; M.H. and E.I.: writing original draft preparation; M.H. and E.I.: writing review and editing. M.H. and E.I., visualization; A.R. and B.M.: supervision. All of the authors have read and agreed to publish this version of the manuscript.

References

[1] Pye D, Practical nitriding and ferritic nitrocarburizing, ASM International. 2003.
[2] Nolan A, et al. ASM handbook volume 3 - alloy phase diagrams. ASM Internationa,1992; 3.
[3] Aligizaki D.K, Surface engineering for corrosion and wear resistance. Vol. 51, No. 1.; 2004.
[4] Beregovenko A.Y, Kaplun V.G, Yakovlev A.P, Pastukh I.N, Influence of nitriding on damping properties of some metallic materials. Strength Mater. 1993; 8: 604–9.
[5] Nakanishi T, Tsuchiyama T, Mitsuyasu H, Iwamoto Y, Takaki S, Effect of partial solution nitriding on mechanical properties and corrosion resistance in a type 316L austenitic stainless steel plate, Mater Sci Eng A. 2007; 460–461:186–94.
[6] Yeh S.H, Chiu L.H, Chang H, Effects of gas nitriding on the mechanical and corrosion properties of SACM 645 steel, Engineering. 2011; 3(9): 942–8.
[7] Fernández Valdés D, Meneses Amador A, Rodríguez Castro G.A, Arzate Vázquez I, Campos Silva I, Nava Sánchez J.L, Standing contact fatigue behavior of nitrided AISI 316L steels, Surf Coatings Technol. 2019; 377: 124871.
[8] Parashar V, Purohit R, Investigation of the effects of the machining parameters on material removal rate using Taguchi method in end milling of steel grade EN19, Mater Today Proc. 2017; 4(2): 336–41.
[9] Yue C, Gao H, Liu X, Liang S.Y, Wang L. A review of chatter vibration research in milling. Chin J Aeronaut. 2019; 32(2): 215–42.
[10] Muhammad B.B, Wan M, Feng J, Zhang W.H, Dynamic damping of machining vibration: A review, Int J Adv Manuf Technol. 2017; 89(9–12): 2935–52.
[11] Huang P, Li J, Sun J, Zhou J, Study on vibration reduction mechanism of variable pitch end mill and cutting performance in milling titanium alloy, Int J Adv Manuf Technol. 2013; 67(5–8): 1385–91.
[12] Dombovari Z, Stepan G, The effect of helix angle variation on milling stability, J Manuf Sci Eng Trans ASME. 2012; 134(5).
[13] Madoliat R, Hayati S, Finite element analysis of a frictionally damped slender endmill. ASME Int Mech Eng Congr Expo Proc. 2013; 3: 1931–9.
[14] Shibata H, Tokaji K, Ogawa T, Hori C, The effect of gas nitriding on fatigue behaviour in titanium alloys, Int J Fatigue. 1994; 16(6): 370–6.
[15] Yang Y, Dai W, Liu Q, Design and implementation of two-degree-of-freedom tuned mass damper in milling vibration mitigation. J Sound Vib. 2015; 335: 78–88.
[16] Mahdikhani B, Javadi M, Experimental study of

the effect of variable pitch in indexable cutting tool on AISI4140 steel surface finish in milling. Adv Mater Process Technol. 2020; 13(3).
[17] Fallah M, Moetakef Imani B, Boring bar chatter control using a novel adaptive direct velocity feedback controller, Iran J Mech Eng Trans ISME. 2021; 23(1): 85–109.
[18] CNS: 14288-G2272. 2006; 1–6.