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Numerical Modeling and Optimization of Nomex Honeycomb Core Milling: Influence of Longitudinal and Longitudinal–Torsional Ultrasonic Vibrations

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Abstract: Nomex honeycomb structures (NHCs) have currently experienced significant development, mainly in the aeronautics, aerospace, marine, and automotive sectors. This expansion raises noteworthy challenges related to the improvement of machining excellence, necessitating the use of particular cutting tools and adapted techniques. With this in mind, experimental studies were conducted to analyze the specificities of Nomex honeycomb cores milling by integrating longitudinal ultrasonic vibrations along the cutting tool rotation axis (UCK). However, the high tool speed and the unreachability of the tool-workpiece interface complicate the direct observation of the cutting process. To overcome these challenges, a 3D numerical model was developed to simulate the milling of composite honeycomb structures by integrating longitudinal and longitudinal–torsional ultrasonic vibrations. This model was developed by Abaqus/Explicit software, version 2017. The obtained results indicate that the integration of longitudinal–torsional vibrations allows a reduction in cutting forces by up to 28%, a reduction in the accumulation of material in front of the cutting tool, with a maximum reduction of 30%, and an improvement in the quality of the machined surface.

Keywords: numerical modeling; Nomex honeycomb structure (NHC); longitudinal ultrasonic vibration; longitudinal–torsional ultrasonic vibration; surface quality; cutting force; chips formation

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1. Introduction

Nomex honeycomb structures (NHCs) are made of aramid fibers impregnated with phenolic resin, which gives them excellent mechanical properties, high toughness, and notable chemical resistance [1–3]. Due to these exceptional characteristics, Nomex honeycomb structure cores find wide application in the aeronautics and aerospace sectors, particularly in the design of aircraft wings and empennages [4–7]. Machining Nomex honeycomb structures poses a significant challenge for researchers and engineers due to their complex geometry and the heterogeneous nature of the material. For this purpose, detailed experimental studies were carried out to better understand and analyze the particularities of machining Nomex honeycomb structures. These studies provide essential data for the development of advanced numerical models, intended to simulate the behavior during machining and to optimize the operating parameters [8,9]. The Nomex honeycomb core is generally machined using conventional techniques, using specific cutting tools. However, despite the existence of machining tools specially designed for this type of structure, the conventional methods present notable limitations in terms of precision and quality of the obtained surfaces. The machined surface of the Nomex honeycomb core may exhibit defects such as burrs, cellular deformations, and tears of the aramid fibers [10], which makes conventional machining techniques insufficient to effectively handle these features and compromises the quality of the resulting surface. In order to overcome these limitations, it is crucial to develop more advanced machining techniques, specially adapted to the honeycomb composite structure, and to optimize the cutting parameters to reduce cell deformation and fiber tearing. In this context, a new technology called RUM has been introduced as an effective solution to overcome the challenges of conventional machining processes applied to Nomex honeycomb structure. This technology is distinguished by the application of ultrasonic vibrations along the tool axis, thus allowing better control of cell deformation and optimized cutting of aramid fibers [11–14]. RUM technology is attracting increasing attention for the machining of various materials, whether conductive or dielectric. These materials include titanium alloys [15,16], aluminum alloys [17–20], nickel alloys [21,22], glass [23,24], ceramics [25,26], and composite materials [27–30]. A large number of researchers have conducted studies on the milling of honeycomb materials. As an example, Xia et al. [31] conducted a study to optimize the structural design of an ultrasonic circular disk tool, analyzing the influence of its geometric characteristics on the energy density, tool stiffness, and machining efficiency of Nomex honeycomb cores, which closely depend on different parameters such as rake angle, tool radius, and vibration amplitude. In this sense, Sun et al. [32] demonstrated the advantages of RUM technology in the machining of honeycomb metal structures, showing that this technique reduces the forces exerted by the tool, which allows limitation of the plastic deformation of the structure. Also, Ahmad et al. [33] developed an innovative model of a disk milling cutter equipped with saw-shaped teeth and studied, using finite element simulations and experiments, the influence of various structural parameters of this tool on its resonance frequency. The obtained results highlighted that the frequency and amplitude of the ultrasonic vibrations generated by this tool are adequate for the ultrasonic machining of Nomex honeycomb core. Another approach for machining Nomex honeycomb structures is to apply longitudinal–torsional ultrasonic vibrations to the milling cutter. Several experimental studies have been conducted on this process in the literature. As an example, Xiang et al. [34] studied a longitudinal–torsional ultrasonic-vibration-assisted machining process applied to Nomex honeycomb structures. The experimental results demonstrated that this technique can reduce the cutting force compared with machining assisted only by longitudinal vibrations. In addition, it was found that the spindle speed plays a determining role in the evolution of the cutting force. Finally, this process also makes it possible to reduce burrs and tear defects, while improving the surface quality of honeycomb core composites, especially when the spindle speed is increased. Although experimental testing remains essential for the machining of Nomex honeycomb cores, numerical modeling is becoming increasingly important to better understand this process. It allows the study of complex configurations and conditions that are difficult to measure experimentally. Numerical modeling of the machining of honeycomb structures using RUM technology remains a booming field of research, marked by a scarcity of in-depth numerical studies. In this perspective, several numerical studies available in the literature have focused on the use of longitudinal ultrasonic vibrations to improve the machining of honeycomb structures [35,36]. The results of this work demonstrate that the application of ultrasonic vibrations makes it possible to optimize cutting forces while improving the quality of the machined surface. Although this work provides a better understanding of some of the mechanisms associated with this technique, it still presents significant limitations, particularly in terms of precision, consideration of complex interactions between the tool and the structure, and modeling of thermomechanical phenomena. Therefore, a three-dimensional numerical machining model was developed using Abaqus/Explicit software, integrating longitudinal and torsional ultrasonic vibrations to simulate the cutting process and analyze essential parameters such as cutting forces and surface quality. The analysis allowed us to characterize the effect of combined ultrasonic vibrations on these parameters, opening new perspectives for the optimization of the machining of honeycomb structures.

2. Materials and Methods: Description of Equipment and Experimental and Numerical Approaches

This numerical study focuses on the integration of ultrasonic vibrations in the machining process of Nomex honeycomb structures. First, the numerical model was validated using longitudinal ultrasonic vibrations, allowing us to evaluate their influence on machining performances, particularly the reduction in cutting forces. The extension of this study allows the integration of longitudinal–torsional vibrations, thus providing an in-depth analysis of the complex interactions between vibrations and cutting dynamics, and highlighting the specific challenges associated with machining alveolar core walls. The main objective of this paper is to evaluate the combined effect of these vibrations on the cutting forces, the accumulation of chips in front of the cutting tool, and the generated surface. To validate the numerical model, our study focuses on experimental work on milling honeycomb structures, carried out using RUM technology with the THU Ultrasonic 850 machine developed by Tsinghua University [37]. This system features notable performance features, including 2 kW power, spindle speed of up to 10,000 rpm, and maximum vibration amplitude of 27 µm. In this study, the machined part is a Nomex honeycomb (NHC) structure, composed of aramid fibers and phenolic resin. Due to its brittleness, its machining presents technical challenges and requires special precautions to avoid damage. The geometric dimensions of the NHC structure as well as the cell are shown in Figure 1 while the mechanical properties of the Nomex paper are specified in Table 1.

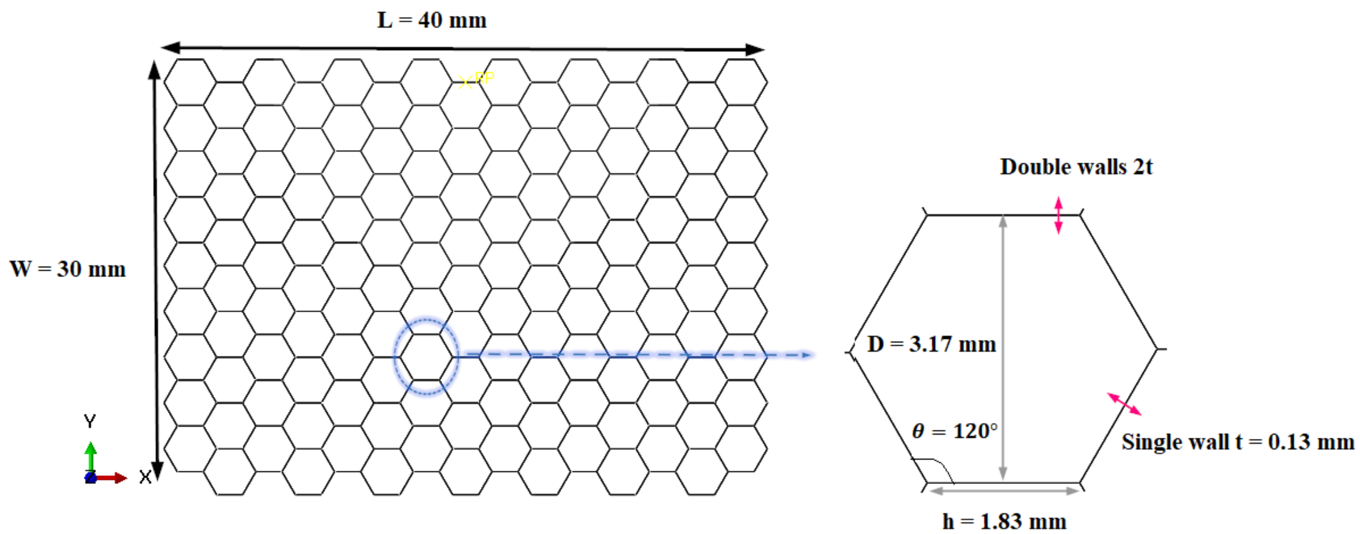

Figure 1. Double-walled hexagonal structure with geometric characteristics and dimensions.

Table 1. The mechanical properties of Nomex paper [38].

Density (g/cm^3)	Young's Modulus (MPa)	Poisson's Ratio
1.4	3400	0.3

The machining of the Nomex honeycomb core was carried out using a specific cutting tool, called UCK. The latter is an ultrasonic circular milling cutter made of high-speed steel (HSS-W18Cr4V), chosen for its hardness and increased wear resistance. The design of this tool has been carefully optimized to fit the geometric dimensions of honeycomb structures and to meet the requirements of experimental constraints, as illustrated in Figure 2.

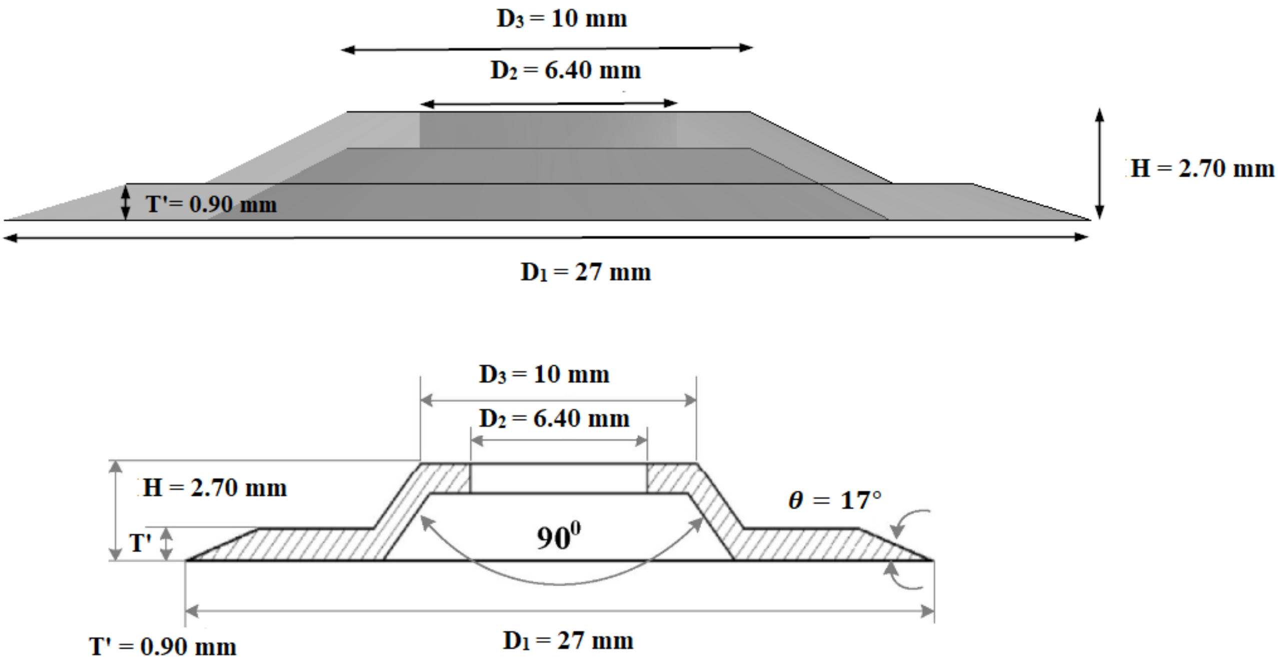

Figure 2. The geometric dimensions of the UCK cutting tool [37].

3. Ultrasonic-Vibration-Assisted Milling: Principle and Approach

Ultrasonic-vibration-assisted machining is based on the application of a high-frequency periodic motion, usually applied to the cutting tool, although in some cases it can be applied to the workpiece. This technique allows us to modify the classic machining conditions by introducing ultrasonic vibrations that improve the precision, efficiency, and quality of the cut. Ultrasonic-vibration-assisted milling offers great flexibility for machining parts with various shapes and dimensions, thanks to its stability and precise vibration control. This process reduces cutting forces, improves tool life, and optimizes overall machining performance. In the specific context of longitudinal–torsional ultrasonic milling, a three-dimensional motion is generated at the tool cutting edge, which results in better interaction between the tool and the workpiece, thus reducing the risk of unwanted vibrations and machining defects. This approach forms the basis of the study explored in this paper. In this context, the reference axes are defined as follows: The Y axis corresponds to the feed direction, the X axis represents the radial cutting depth, and the Z axis denotes the axial cutting depth. For conventional milling processes, the cutting-edge trajectory is modeled by the following equation [39]:

$$\begin{cases} x(t) = V_f t + r\,cos(\frac{2\pi nt}{60}) \\ y(t) = r\,sin(\frac{2\pi nt}{60}) \\ z(t) = 0 \end{cases} \tag{1}$$

where V_f represents the feed rate of the tool, expressed in mm/min, n corresponds to the spindle speed, given in rpm, and r denotes the tool radius, in mm.

Unlike traditional milling processes, longitudinal–torsional ultrasonic milling incorporates combined longitudinal and torsional vibrations. In this study, a uniquely excited helical groove horn allows the frequencies of these vibrations to be precisely synchronized, ensuring a coherent interaction between the two vibration modes and optimizing the dynamic behavior of the cutting tool. The mathematical expression for the longitudinal displacement of the cutting edge is

$$z(t) = A\,sin\,(2\pi f t) \tag{2}$$

In the previous equation, f represents the frequency of the ultrasonic vibration, expressed in Hz, while A represent the amplitude of the longitudinal ultrasonic vibration in mm.

Ultrasonic longitudinal–torsional vibration-assisted cutting can be seen as a combination of classical cutting, using a disk tool subjected to ultrasonic longitudinal vibrations along the tool axis, as well as ultrasonic torsional vibrations in the direction of tool rotation. Thus, the trajectory of the disk tool movement during the cutting process assisted by longitudinal and torsional ultrasonic vibrations can be formulated as follows [34]:

$$\begin{cases} x_1(t) = V_f t + r\,cos(\frac{2\pi n t}{60} + A\ \sin\,(2\pi f t)) \\ y_1(t) = r\,sin(\frac{2\pi n t}{60} + A\ \sin\,(2\pi f t)) \\ z_1(t) = A\sin(2\pi f t + \varphi_0) \end{cases} \tag{3}$$

where A is longitudinal and torsional vibration amplitude. Since the longitudinal vibration and the torsional vibration are generated by the same excitation, they oscillate at the same ultrasonic frequency, denoted by f. φ_0 is the phase difference between longitudinal vibrations and torsional vibrations expressed in Rad.

4. Setting up the Numerical Model

This paper describes a simulation of the cutting process of the Nomex honeycomb structure, assisted by ultrasonic vibrations carried out by means of a 3D digital model developed by the commercial software Abaqus/Explicit. The Nomex honeycomb structure consists of cell walls, of which approximately two-thirds are monocellular (single-walled) and one-third bicellular (double-walled). In the numerical model, the thicknesses of the monocellular and bicellular walls are 0.13 mm and 0.26 mm, respectively. For this purpose, the walls of the honeycomb structure were meshed using four-node S4R shell elements, with reduced integration, as shown in Figure 3a. In the numerical modeling, the UCK tool is treated as a rigid body, assumed to be deformable during the milling operation. Therefore, it is represented using rigid quadrangular elements with four nodes (R3D4), as shown in Figure 3b. The mesh size chosen for the numerical simulations is 0.6 mm. This choice allowed us to achieve an optimal balance between the accuracy of the results and the computational cost. Indeed, this mesh size allowed us to discretize the tool and the structure with a total of 12,481 elements, thus providing sufficient resolution to capture critical details while limiting the computation time. Furthermore, the interaction between the cutting tool and the Nomex honeycomb structure was modeled using an advanced method, based on a penalty function, in order to accurately represent the contact behavior. This technique allows us to accurately model the friction phenomena in the interaction zone, while ensuring appropriate numerical stability for complex simulations. In order to take into account, the effects of ultrasonic vibrations applied to the cutting tool, a dynamic friction coefficient of 0.15 was defined. This choice was based on experimental data and the tribological properties of the interacting structure and reflects the significant reduction in friction induced by ultrasonic vibrations [35]. The walls of the honeycomb structure are made of aramid fiber and phenolic resin. In this study, the Nomex paper is modeled as isotropic elastoplastic. During machining, where the material is cut using a specific tool, it is crucial to define a failure criterion in order to ensure an accurate simulation of the process. These criteria are mainly associated with the fundamental mechanical characteristics of the material. In this study, the shear failure criterion was specifically selected, and its modeling was carried out using the Abaqus finite element analysis software. When the damage coefficient d exceeds a critical threshold of 1 (according to Equation (4)), this indicates material degradation and chip formation.

$$d = \sum \frac{\Delta\varepsilon}{\varepsilon f} \quad (4)$$

where d is damage parameter, $\Delta\varepsilon$ is an increment of the equivalent plastic strain, and ε^f is the equivalent strain at failure.

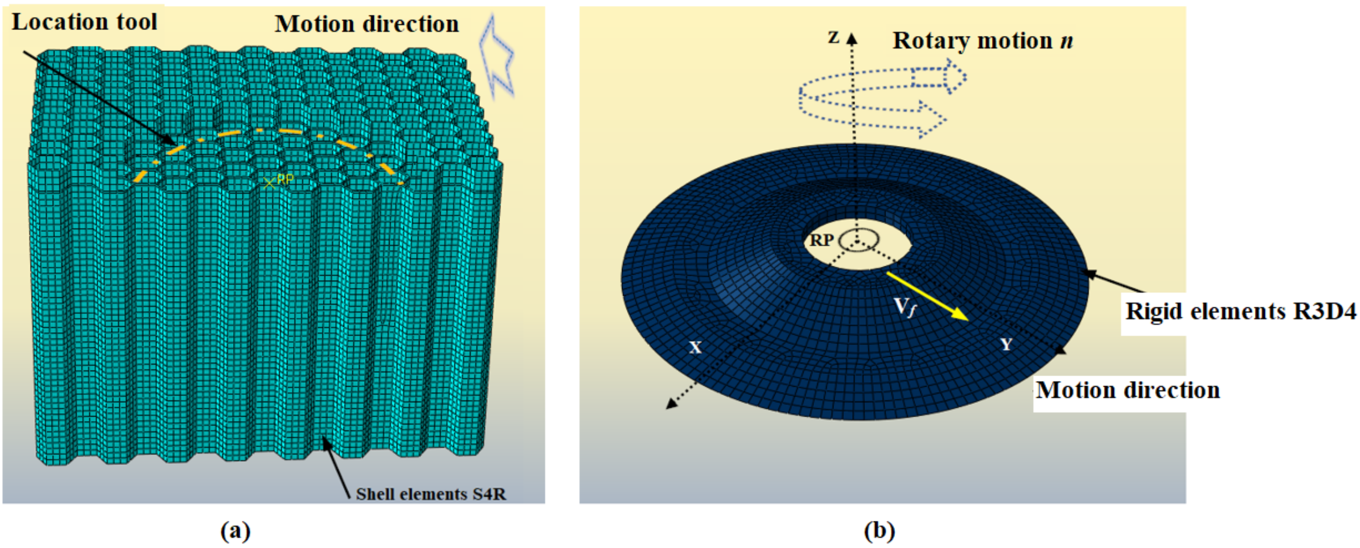

Figure 3. Finite element simulation model of the tool and workpiece: (**a**) mesh of the honeycomb core; (**b**) cutting conditions defined at the reference point RP.

The boundary conditions are defined according to the predefined experimental protocol of [37], and impose a total immobilization of the lower surface of the composite honeycomb core. This constraint, implemented numerically by the cancellation of the translational and rotational degrees of freedom ($U_x = U_y = U_z = U_{Rx} = U_{Ry} = U_{Rz} = 0$), guarantees a faithful reproduction of the physical tests, allowing a precise analysis of the mechanical responses under loading (see Figure 4b). Axial milling assisted by longitudinal and longitudinal–torsional vibrations represents a major advance in the field of high-precision machining. This innovative process combines three fundamental movements in a synergistic manner to optimize machining performance. The first movement is based on the conventional rotation of the tool around the Z axis, defined by a spindle speed n, which ensures material removal. To this rotation are added longitudinal ultrasonic vibrations of frequency f and amplitude A, also applied along the Z axis (Figure 3b). These vibrations, of sinusoidal nature, produce rapid cycles of entry and exit of the tool in the material. In the present study, the cutting process is completed by longitudinal–torsional vibrations of frequency f and amplitude A. These generate a helical movement, combining a translation of the tool along the X axis, linked to the feed rate V_c, and a helical rotation around Z (Figure 4a). In numerical simulations, the reference point (RP), located on the axis of revolution of the tool, makes it possible to precisely follow and analyze its complex movements (rotation, translation, vibrations) (see Figure 3b). This configuration ensures precise modeling of the interactions between the tool, the walls of the structure, and the vibration effects, thus improving the understanding of cutting phenomena assisted by ultrasonic vibrations.

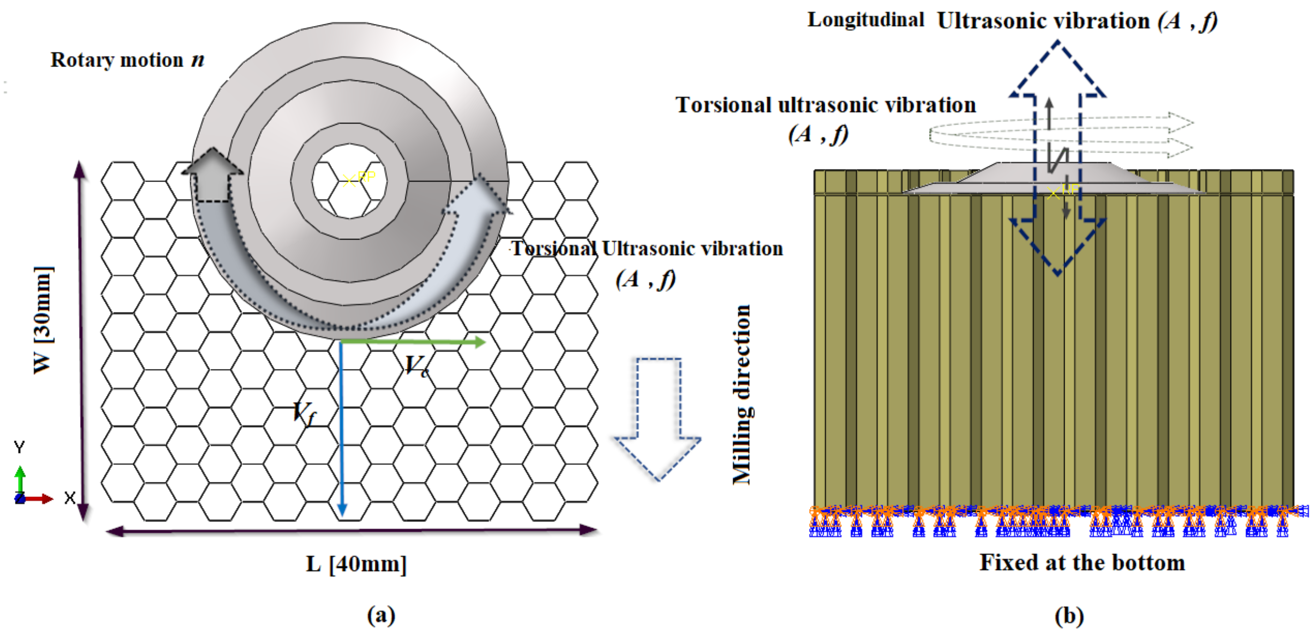

Figure 4. (**a**) Planar representation of the milling process for the honeycomb core; (**b**) boundary conditions applied in the numerical model.

During the experimental phase, the components of the cutting force, designated F_y and F_x, are measured using the KISTLER-9256C2 dynamometer (THU Ultrasonic 850) developed by Tsinghua University of China. The advantage of this method lies in its ability to calculate the average values in both directions, using the following formulas:

$$F_x = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} F_{CX}\, dt \tag{5}$$

$$F_y = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} F_{CY}\, dt \tag{6}$$

F_x and F_y represent the averages of the cutting force components on the X and Y axes, expressed in N, while F_{CX} and F_{CY} denote the instantaneous components of this force, expressed in N. t_1 and t_2 indicate the beginning and end of the cutting process, respectively, expressed in s.

5. Results and Discussion

5.1. Validation of the Numerical Model: Influence of Feed Rate on the Components of Cutting Forces Under Longitudinal and Longitudinal–Torsional Ultrasonic Vibrations

As part of the validation of the numerical model of milling of the Nomex honeycomb structure assisted by the ultrasonic vibrations, simulations were carried out according to the experimental procedure described previously [37]. These simulations allowed us to evaluate the impact of feed rates, varying from 500 to 3000 mm/min, on the cutting force components F_x and F_y. They took into account the effects of longitudinal and longitudinal–torsional ultrasonic vibrations, while maintaining the cutting conditions constant, namely, a spindle speed of 5000 rpm and a cutting depth of 2 mm. Ultrasonic vibrations were applied with a frequency of 21.260 kHz, and the respective amplitudes of longitudinal and longitudinal–torsional vibrations were 25 µm and 14 µm. In order to further validate this numerical model, a comparative study was conducted to analyze the influence of cutting the Nomex honeycomb structure under the effect of two types of vibrations: longitudinal only and longitudinal–torsional. A detailed comparison between numerical and experimental results was performed to evaluate the reliability of the model, as shown in Figure 5.

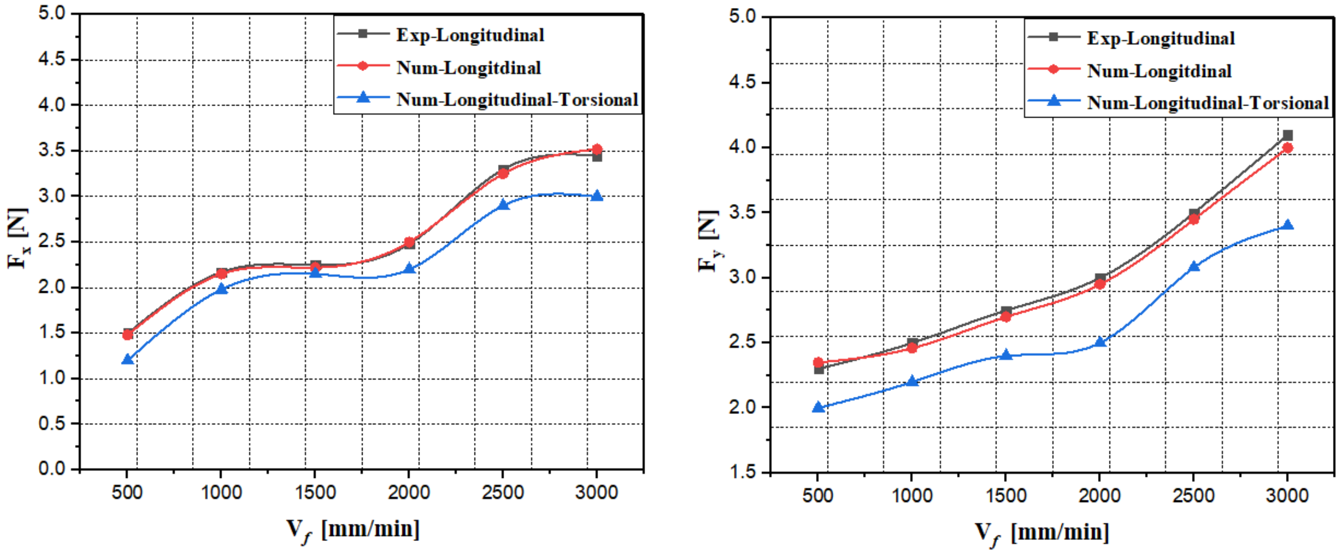

Figure 5. Experimental and numerical cutting forces F_x and F_y under longitudinal and longitudinal–torsional ultrasonic vibrations for different feed rates.

The results presented in Figure 5 indicate a progressive increase in the forces F_x and F_y as a function of the cutting tool feed rate V_f, both in simulation and in experimentation, for the two techniques studied: longitudinal and longitudinal–torsional ultrasonic vibrations. This trend is attributed to the increase in material removed per unit time with increasing V_f. In this regard, it was found that longitudinal–torsional ultrasonic vibrations allowed minimization of the cutting force components F_x by up to 18% and F_y by up to 14%. The elastoplastic behavior of Nomex paper is a key element of the honeycomb structure, which delays the detachment of the cut elements, leading to an accumulation of material in front of the tool and an increase in the apparent resistance of the material. However, the application of ultrasonic vibrations, whether longitudinal or longitudinal–torsional, leads to a significant reduction in cutting forces, with a particularly marked reduction for the combined configuration, as shown by the numerical results. These vibrations reduce the mechanical forces exerted on the tool and the material, thus optimizing the cutting process. The integration of longitudinal–torsional vibrations in the milling of the Nomex honeycomb structure acts on several physical and tribological mechanisms to reduce cutting forces. Longitudinal vibrations decrease continuous contact between the tool and the material, reducing friction, while torsional vibrations fragment the material, facilitating chip detachment. This combination reduces material build-up and improves process efficiency. In addition, the elasticity of Nomex paper, in the absence of vibration, slows down the detachment of the cut elements. However, ultrasonic vibrations break the elastic bonds, accelerating this process and reducing the forces required. Thus, longitudinal–torsional ultrasonic vibrations improve the interaction between the tool and the Nomex honeycomb structure, reducing friction, elastic deformations, and material accumulation. These mechanisms explain the reduction in cutting forces and the efficiency of this technology for milling complex structures. Comparison of numerical and experimental results reveals a significant correspondence, thus highlighting the robustness of the developed numerical model.

5.2. Analysis of the Influence of Rotational Speed on the Components of Cutting Forces Under Longitudinal and Longitudinal–Torsional Ultrasonic Vibrations

This section presents numerical simulations of the milling of a honeycomb composite structure, integrating ultrasonic vibration technology. The main objective of this study is to analyze the impact of different rotational speeds (500 rpm, 1000 rpm, 2000 rpm, 3000 rpm, 4000 rpm, and 5000 rpm) on the force components F_x and F_y, considering ultrasonic vibrations, both longitudinal and longitudinal–torsional. Numerical simulations were performed with a feed rate of 500 mm/min, a longitudinal vibration amplitude of 25 µm, and a cutting depth of 2 mm. The duration of each simulation, corresponding to a cutting width of 2 mm, was 0.24 s. The frequency of ultrasonic vibrations was set at 21.260 kHz, with amplitudes of 25 µm for longitudinal vibrations and 14 µm for longitudinal–torsional vibrations. In this context, a comparative study was conducted to evaluate the influence of ultrasonic vibrations on the cutting of the Nomex honeycomb structure. Two configurations were examined: cutting assisted only by longitudinal ultrasonic vibrations and cutting integrating longitudinal–torsional vibrations. A detailed analysis was performed to compare the numerical results with the experimental tests, in order to verify the accuracy and reliability of the proposed model. The results of this comparison are presented in Figure 6.

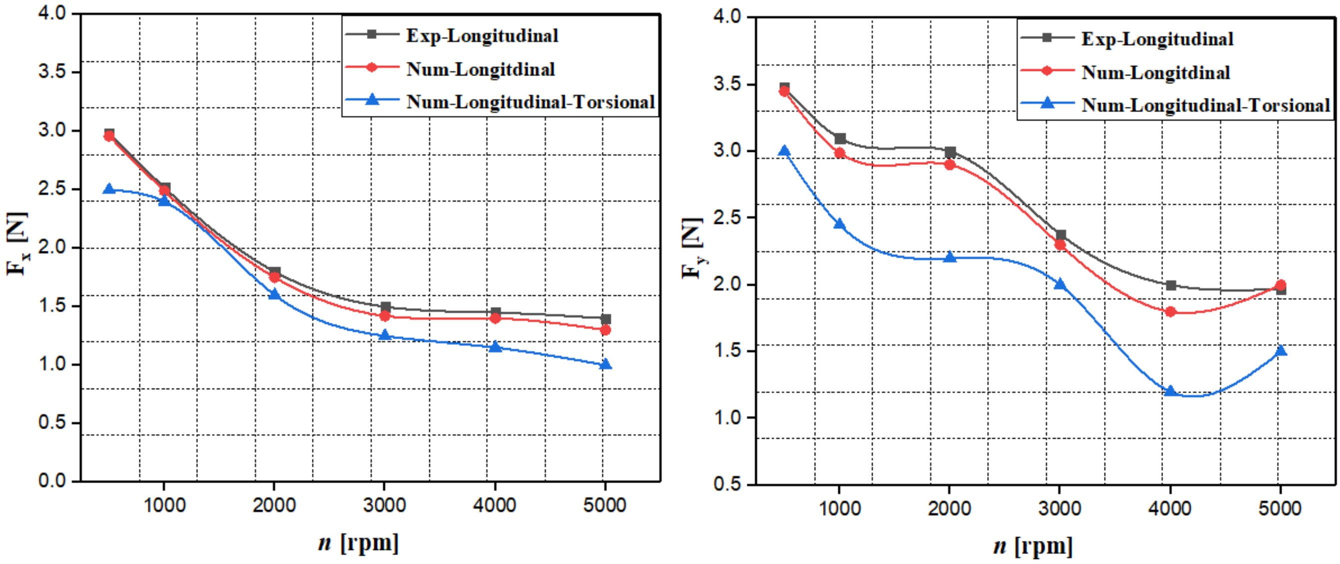

Figure 6. Experimental and numerical cutting forces F_x and F_y under longitudinal and longitudinal–torsional ultrasonic vibrations for different rotational speeds.

The obtained results from the two proposed approaches show a general trend consistent with experimental observations: the cutting force components decrease as the spindle speed increases. At low speeds, the forces F_x and F_y are high, mainly due to the accumulation of chips in front of the tool. This phenomenon is attributed to the elastic deformation of the Nomex paper, which promotes the accumulation of material before the honeycomb walls break. On the other hand, at very high spindle speeds, the increased interaction between the tool and the material can induce undesirable effects, further complicating the cutting process. However, the improvement of the cutting mechanism at high speeds can be observed due to a limited contact between the tool and the honeycomb walls. This reduced interaction allows a decrease in local stresses, thus promoting a more efficient cutting. Moreover, the introduction of longitudinal–torsional ultrasonic vibrations into the cutting process significantly improves the efficiency of the process compared to the use of longitudinal vibrations. Based on the numerical results, it is observed that longitudinal–torsional ultrasonic vibrations allow a reduction in the cutting force components F_x up to 28% and F_y up to 25%. Torsional vibrations generate complex physical mechanisms that influence the cutting force components along the X and Y axes. In particular, the tangential force component F_y is significantly reduced thanks to the torsional vibrations, which increase the lateral micro-displacements of the tool. This action promotes more precise cutting and limits the accumulation of material, which reduces the resistance to tool feed, especially at low rotation speeds, where chip accumulation is more marked. Similarly, torsional vibrations cause a redistribution of mechanical stresses in the material, thus reducing the normal force component F_x. This phenomenon facilitates the rupture of the honeycomb walls and reduces the areas of stress concentration, leading to a smoother and less aggressive cut. In conclusion, the combination of the reduction in the forces F_x and F_y contributes to a notable improvement in the overall efficiency of the machining process. This optimization not only reduces the stresses exerted on the tool, but also promotes heat dissipation and limits tool wear. These effects are particularly important in the context of Nomex honeycomb structures, whose complex geometry can accentuate local forces and make the machining process more difficult.

5.3. Impact of Ultrasonic Vibrations on Chip Accumulation and Cutting Dynamics

Chip accumulation in front of the cutting tool is a major challenge in machining processes, especially in manufacturing. This phenomenon disrupts the cutting motion and generates unwanted vibrations, which can lead to several technical problems. These vibrations can not only impair the quality of the machined surface, but also accelerate the wear of the cutting tool, reducing its life and increasing production costs. Effective management of this accumulation is, therefore, crucial to optimize the performance of the machining process. In order to better understand the mechanisms associated with this phenomenon, this study uses numerical simulations. These were conducted to compare the impact of longitudinal–torsional ultrasonic vibrations with those of longitudinal ultrasonic vibrations alone on chip formation and accumulation. The main objective of this analysis is to examine to what extent the addition of torsional vibrations, combined with longitudinal vibrations, modifies the cutting dynamics, in particular by reducing the accumulation of material in front of the tool. For this study, unfavorable cutting conditions were chosen in the previous experimental and numerical phases. Specifically, a spindle speed of 5000 rpm, a feed rate of 3000 mm/min, and a vibration amplitude of A = 5 µm were applied. The duration of each simulation was set to 0.06 s, which corresponds to a cutting width of 3 mm. The obtained results are shown in Figure 7.

The machining of honeycomb cores can be modeled as a two-phase dynamic process. In the first phase, the cutting tool penetrates the thin walls of the structure, causing a displacement of the material towards the active cutting zone. At this stage, the high spindle rotation speed generates chipping forces that cause chip expulsion. This interaction between the material geometry and the tool parameters, especially the spindle rotation speed, influences the cutting mechanisms, introducing complex dynamics related to the forces generated during the contact between the tool and the material. In this study, the simultaneous integration of longitudinal and torsional ultrasonic vibrations during the milling of honeycomb structures has considerable advantages over the exclusive use of longitudinal vibrations. It was observed that this combination allows a significant reduction in the accumulation of chips in front of the cutting tool, with a decrease of about 30%, according to the results obtained by the bare OEL. Longitudinal vibrations, which generate a linear oscillation along the axis of the cutting tool, reduce cutting forces and facilitate chip evacuation by reducing friction between the tool and the material. However, their effect remains limited to the longitudinal direction, which can lead to material build-up in front of the tool, especially when milling hard materials or complex structures such as honeycomb cores. By introducing torsional vibrations in addition to longitudinal vibrations, the tool benefits from an additional oscillating motion that improves the distribution of cutting energy and further reduces material build-up. This approach not only improves cutting performance, but also extends tool life while optimizing the quality of the machined surface. Adding torsional vibrations to longitudinal vibrations allows the introduction of additional oscillation perpendicular to the cutting axis, which contributes to a further reduction in cutting forces. These torsional vibrations generate micro-oscillations that break down the material more efficiently, facilitating chip ejection and limiting material build-up in front of the tool. This phenomenon is particularly beneficial when milling honeycomb structures, such as NHC materials, whose geometry and low density make material removal particularly difficult. Thus, the combined use of longitudinal and torsional vibrations optimizes the machining process by reducing cutting forces, while improving milling efficiency, tool life, and surface quality. This approach enables more precise and energy-efficient milling, providing better process control compared to the exclusive use of longitudinal vibrations.

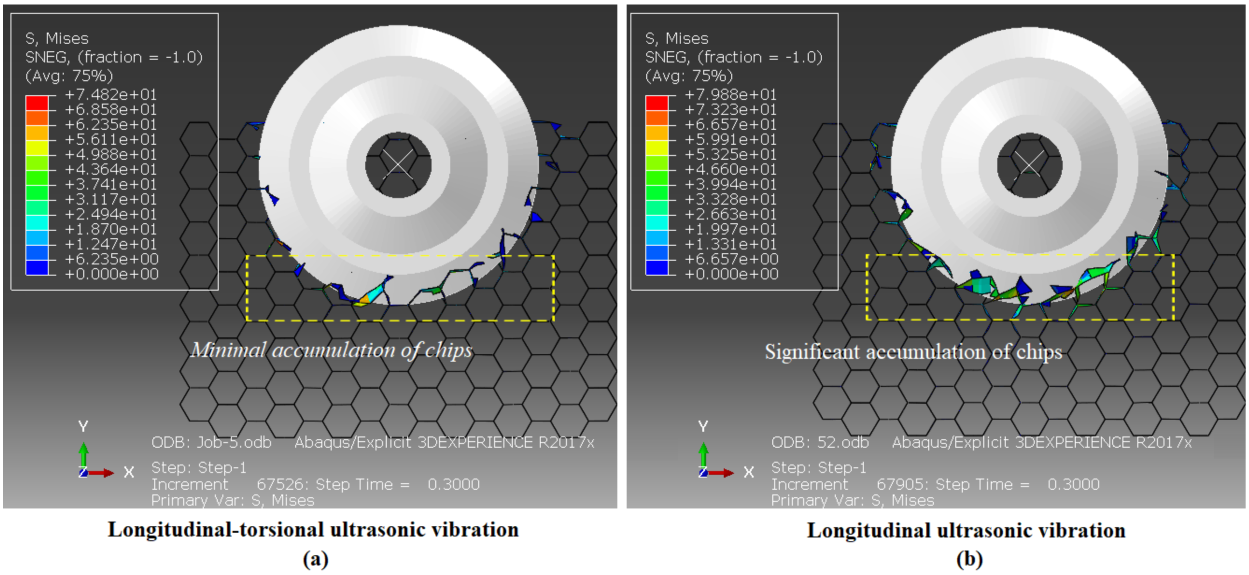

Figure 7. Chip accumulation at the front of the cutting tool: (**a**) Under longitudinal–torsional ultrasonic vibration; (**b**) under longitudinal ultrasonic vibration.

5.4. Analysis of the Impact of Longitudinal–Torsional Ultrasonic Vibrations on the Quality of the Machined Surface

The machined surface of the Nomex honeycomb core is of dominant rank in the manufacturing of sandwich structures. Optimizing this surface is essential to ensure the performance, robustness, and durability of materials in industry. Indeed, failures can appear during the machining of composite honeycomb structures, in various forms such as burrs, wall tears, or uncut fibers. These defects can occur at different stages of the manufacturing process and, if not controlled, can compromise the quality and reliability of the final structure, thus affecting its suitability for the requirements of industrial applications. In this framework, a numerical study was conducted to analyze the impact of longitudinal–torsional ultrasonic vibrations on the quality of the machined surface, in comparison with the effect of longitudinal ultrasonic vibrations alone. For this analysis, two amplitudes of ultrasonic vibrations, namely, 10 µm and 25 µm, were considered for both configurations. The cutting conditions used in these simulations included a feed rate of 3000 mm/min and a spindle speed of 1000 rpm. The machining defects observed in the numerical model results, which were confirmed by visual inspection, are shown in Figure 8.

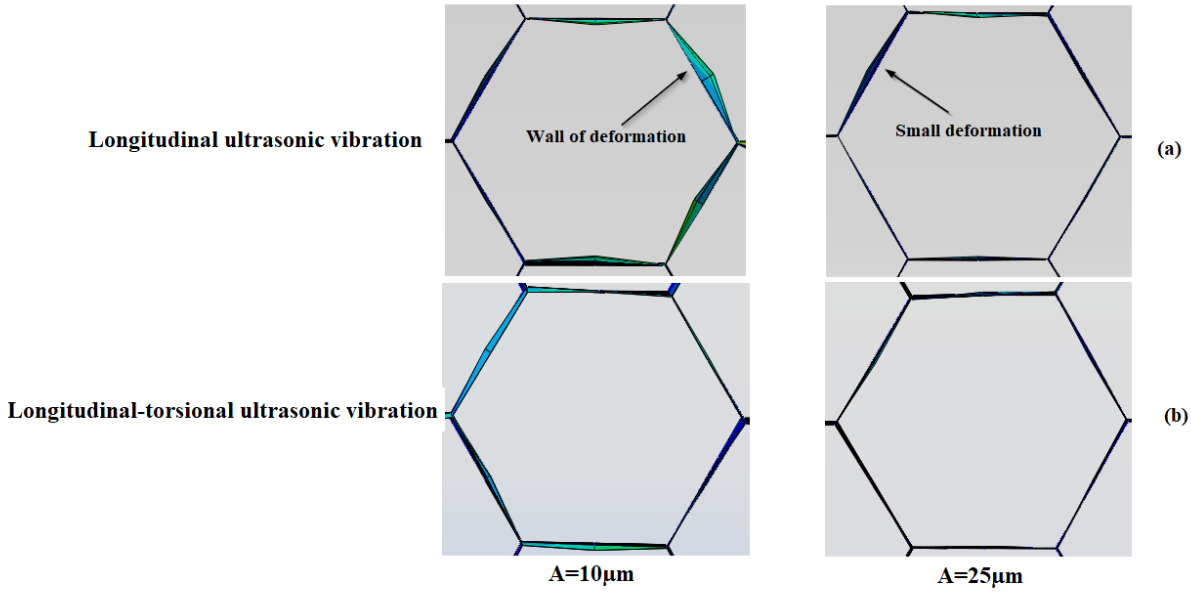

Figure 8. Evolution of the machined surface based on vibration amplitude: (**a**) Longitudinal ultrasonic vibration; (**b**) longitudinal–torsional ultrasonic vibration.

The main results of this study reveal a progressive improvement in the quality of the machined surface as the amplitude of the ultrasonic vibrations increases. This observation suggests a direct correlation between the amplitude of the vibrations and the quality of the surface, thus highlighting the potential benefits of integrating this technique into machining processes. The integration of longitudinal–torsional ultrasonic vibrations in the milling of Nomex honeycomb structures offers a significant improvement in the quality of the machined surface compared to the exclusive use of longitudinal ultrasonic vibrations. This improvement is explained by the combined mechanisms of the two vibration modes. Longitudinal vibrations, oriented in the cutting direction, allow a reduction in machining forces by facilitating the detachment of fibers and material walls. However, their effect is mainly one-dimensional, which can lead to areas of irregularities or residues in directions perpendicular to the cut. On the other hand, the addition of torsional vibrations, which generate a high-frequency rotary motion around the tool axis, induces a multidirectional cutting action. This rotary motion improves the contact between the tool and the material, promoting a more homogeneous material removal and reducing the phenomena of burrs, tears, or uncut fibers. In addition, this synergy between longitudinal and torsional vibrations minimizes the accumulation of material in front of the tool, thus limiting defects related to the elastic deformation of the honeycomb core walls. As a result, the integration of longitudinal–torsional ultrasonic vibrations produces a smoother and more uniform machined surface, with a significant reduction in imperfections, making it a more efficient technique for machining Nomex honeycomb structures.

6. Conclusions

This study highlighted the effectiveness of integrating longitudinal and longitudinal–torsional ultrasonic vibrations in the milling of Nomex honeycomb structures. The numerical model developed with Abaqus/Explicit allowed us to accurately simulate the machining process and to analyze the effects of vibrations on critical parameters such as cutting forces, chip formation, and surface quality. The main results show the following:

- The components of the cutting force F_x and F_y decrease with high rotation speeds and increase with higher feed rates. The integration of longitudinal–torsional vibrations allows a reduction in these cutting forces by up to 28% compared to the exclusive use of longitudinal vibrations. The obtained results both numerically and experimentally confirm the reliability of the proposed numerical model.

- The combined approach of longitudinal and torsional vibrations has proven to be more effective than longitudinal vibrations alone in reducing the cutting force components F_x and F_y. This reduction in cutting forces limits tool wear, extends tool life, and significantly improves the efficiency of the machining process.
- Longitudinal–torsional vibration offers a substantial improvement over longitudinal vibration, effectively reducing material build-up in front of the cutting tool. This optimization, which can reach up to 30%, prevents chip formation on the tool edge, thus limiting wear related to material sticking.
- Longitudinal–torsional ultrasonic vibrations significantly improve the obtained surface quality, reducing defects related to the machining process and promoting a more uniform and precise finish.
- In perspective, we hope to validate the numerical model by experimental tests, with particular emphasis on the quality of the machined surface and the wear of the cutting tool. This study will allow us to confirm the effectiveness of the longitudinal–torsional approach and to better understand its impacts on the machining performances in real conditions.

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