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Modification of CNC Machine Tool Operations and Structures Using Finite Element Methods: A Review

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Abstract

To increase accuracy as well as productivity in CNC machine tools, Finite Element Methods (FEM) are applied to the machining operations and machine tool structures. As a result, the errors of machining operations can be analyzed and minimized in order to enhance accuracy of machined parts. Also, by analyzing the stress and deformations of the machine tool elements under actual loads, performances as well as working life of the machine tool structures can be enhanced. The study reviews the analysis and modification of CNC machine tool operations and structures using finite element methods from the recent published papers. Applications of the FEM methods in the simulation of cutting temperatures, cutting forces and energy consumption, chip formation, deflection and deformation errors of thin-walled components, and tool wear rate during machining processes are reviewed to demonstrate the capabilities of the FEM simulation in CNC machining modification. Furthermore, applications of theFEM tosimulate various machine tool components such as the bed, ball screw, spindle, and guideways are studied in order to enhance the performances of various machine tool elements such as mechanical properties in real-world working situations.In order to fill the gaps between the existing studies and published papers, innovative concepts and approaches of future research works are also suggested. Thus, the research field can be developed by reviewing and analyzing previous achievements in published research works in order to offer innovative concepts and approaches in applications of FEM techniques in modifying machining procedures and CNC machine tool structures.

Keywords: Finite Element Methods, CNC Machine Tools, Machining Operations, Machine Tool Structures.

1. Introduction

Numerical method for estimating partial differential equation (PDE) and integral equation solutions is the finite element method (FEM). The strategies of finding solutions in FEM are based on either totally getting rid of the differential equation or converting the PDE into an approximation system of ordinary differential equations. The method is then computationally integrated using methods like Euler's and the Runge-Kutta procedure in order to enhance the power of analysis and modification in different engineering applications[1]. In order to improve accuracy and productivity in the processes of producing parts utilizing machining operations, finite element analysis (FEA) can be employed [2, 3]. The FEM can be used to model the behavior of CNC machine tool structures and operations in order to improve performance of CNC machine tools in process of part manufacturing[4].

To create the accurate analysis of metal cutting operations, several criteria and variables should be considered during evaluation process. It is challenging to analyse and modify the metal cutting operations using experimental works which needs several attempts and reputations to decrease the errors of experiments [5, 6].

Thus, a simulation technique which can accurately predict performance of machine tool is required in order to compute massive motions on flexible CNC machine tool structures in order to analyse and modify the machining outcomes during CNC machining operations [7, 8].

FEM can be used to optimize the machining process by simulating the cutting forces and tool deflection in order to reduce tool wear and improve surface quality of machined parts[9]m. The features of the tool's tip, rake, and flank angles, and cutting speed, have a significant impact on energy consumption, tool wear rate, and material removal rate during machining operations. Thus, to minimize time and cost of part productions using CNC machining operations, FEM can identify the optimal machining conditions for a given material and cutting tool conditions by optimizing the cutting parameters such as spindle speed, feed rate, and depth of cut and cutting tool specifications. To integrate cutting process simulation using the finite element approach, a novel machining forces prediction method can be created using FEM simulation [10]. Another application of FEM is in the development of adaptive control systems, which use real-time

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sensor data to adjust the machining parameters during operation[11]. FEM can be used to model the behavior of the machining process and predict the effects of various control inputs, allowing for the development of more accurate and effective control systems.

FEM simulation of chip generation process can also be implemented in order to decrease the cost of experimental works in terms of CNC cutting process modifications. Cutting temperature, cutting forces, energy consumption, strain rate and residual stress during chip formation process can be accurately predicted and analyzed using FEM approaches in order to enhance the productivity in process of part production using CNC machining operations [12, 13]. By extending the life of the cutting tool and reducing machining time during CNC machining operations, it is possible to minimize cost of part production [14]. To provide accurate parts in advanced manufacturing processes, accuracy as well as performances of CNC machine tools can be monitored using FEM simulation[11].

FEM is a powerful tool for designing and modifying CNC machine tool structures. It allows engineers to simulate the behavior of the structure under different loading conditions, identify areas of potential failure or deformation, optimize the design for specific performance criteria, and improve the dynamic performance of the machine tool[15]. During the design stages of CNC machine tool structures, simulation technologies such as FEM can be implemented in order to reduce try-and-error stages. FEM allows engineers to gain a better understanding of the behavior of machine tool structures under various loading conditions. It allows engineers to analyze the response of complex structures to various loads and boundary conditions with a high degree of accuracy. Overall stability of machine tools as well as accuracy of final parts using CNC machine tools are under influence of machining stiffness which should be analyzed in terms of productivity enhancement of part production [16]. FEM can be used to optimize the design of machine tool structures by evaluating different designs and selecting the one that performs best in terms of stiffness, vibration, and stress. Also, the dynamic behaviour of the CNC machine tool during machining operations is restricted by key performance parameters which is necessary to be considered during the designing phase of CNC machine tools structures [17]. FEM can help to reduce the cost of machine tool structure design by eliminating the need for expensive physical prototypes. FEM simulation enables engineers to quickly evaluate different design alternatives and make design changes without the need for physical prototypes. So, the FEM simulation results can help engineers to analyze and develop the designing stage of machine tool structures in order to minimize cost and time of accurate production using CNC machine tools[18]. FEM model of twin ball screw worktable. (a) FEM modelof ball screw and nut; (b) FEM modelof angular contact bearing; (c) FEM model of linear guide; (d) FEM model of whole Twin ball screw system is shown in the figure 1 [19].

To maintain accuracy and precision during milling operations, it is crucial to analyse and optimize the dynamic properties of machine tools using the FEM methods[20]. Finite-element analysis and simulation of machining are reviewed to provide the key topics of the applied FEM methodologies to the CNC machining modifications [21].Soori et al. suggested virtual machining techniques to evaluate and enhance CNC machining in virtual environments [22-25]. Soori and Asamel[26]examined the implementation of virtual machining technology to minimize residual stress and displacement error throughout turbine blade five-axis milling procedures.Soori and Asmael[27] explored applications of virtualized machining techniques to assess and reduce the cutting temperature throughout milling operations of difficult-to-cut objects.Soori et al. [28] indicated an advanced virtual machining approach to improve surface characteristics throughout five-axis milling procedures for turbine blades. Soori and Asmael[29]created virtual milling processes to reduce displacement error throughout five-axis milling operations of impeller blades. In order to analyze and develop the process of part production in virtual environments, virtual product development is presented by Soori[30]. Soori and Asmael[31]proposed an overview of current advancements from published research to review and enhance the parameter technique for machining process optimization. In order to improve the efficiency of energy consumption, the quality and availability of data across the supply chain, and the accuracy and dependability of component manufacture, Dastres et al. [32]proposed a review of RFID-based wireless manufacturing systems.Soori et al. [33] explored machine learning and artificial intelligence in CNC machine tools to boost productivity and improve profitability in production processes of component employing CNC machining operations. To improve the performance of machined components, Soori and Arezoo[34]reviewed the topic of measuring and reducing residual stress in machining operations. To improve surface integrity and decrease residual stress during Inconel 718 grinding operations, Soori and Arezoo[35] proposed the optimum machining parameters employing the Taguchi optimization method. In order to increase the life of cutting tools during machining operations, Soori and Arezoo[36] examined different method of tool wear prediction algorithms. Soori and Asmael [37] investigated computer assisted process planning to boost productivity in the part manufacturing procedure. Dastres and Soori [38]reviewed applications of artificial neural networks in different sections, such as analysis systems of risk, drone navigation, evaluation of welding, and evaluation of computer simulation quality, to explore the execution of artificial neural networks for improving the effectiveness of products. Dastres and Soori[39]proposed employing communication system in environmental concerns to minimize the negative effects of technological advancement on natural catastrophes. To enhance network and data online security, Dastres and Soori[40] suggested the secure socket layer. Dastres and Soori[41] studied the developments in web-based decision support systems to develop the methodology of decision support systems by evaluating and suggesting the gaps between proposed approaches. To strengthen network security measures, Dastres and Soori[42] discussed an analysis of recent advancements in network threats in order to enhance security in web of data. To increase the potential of image processing systems in several applications, Dastres and Soori[43] evaluated image processing and analysis systems.Dimensional, geometrical, tool deflection, and thermal defects have been modified by Soori and Arezoo[44] to improve accuracy in 5-axis CNC milling processes. Recent developments in published articles are examined by Soori et. al. [45] in order to assess and improve the impacts of artificial intelligence, machine learning, and deep learning in advanced robotics. Soori and Arezoo[46]developed a virtual machining system application to examine whether cutting parameters affect tool life and cutting temperature during milling operations. Soori and Arezoo[47] studied the impact of coolant on the cutting temperature, roughness of the surface, and tool wear during turning operations with Ti6Al4V alloy. Recent developments from published papers are reviewed by Soori[48] in order to examine and alter composite materials and structures. Soori et al. [49] examined the Internet of things application for smart factories in industry 4.0 to increase quality control and optimize part manufacturing processes. To minimize cutting tool wear during drilling operations, Soori and Arezoo[50] designed a virtual machining system. Soori and Arezoo[51] decreased residual stress and surface roughness in abrasive water jet machining in order to improve the quality of produced parts.

Machine tool structure simulation and metal cutting modelling using finite element methods are closely linked in the field of manufacturing engineering. The behavior of the machine tool structure affects the metal cutting process, where the performance of machine tool structure is under influence of parameters of metal cutting operations. Thus, it is possible to optimize the machining process and achieve better overall performance by simulating both the machine tool and the metal cutting process using finite element methods.

Analysis and modification of CNC machine tool operations and structures using finite element methods are reviewed in the paper. Applications of the FEM methods in simulation of cutting temperatures, cutting forces and energy consumption, chip formation, deflection and deformation errors of thin walled components, and tool wear rate during machining processes from the recent published papers is reviewed in order to provide the capabilities of the FEM simulation in CNC machining modification. Moreover, to improve the performances of various machine tool elements under actual working conditions, finite element methods are applied. Different machine tool elements such as machine tool bed, ball screw, spindle, and guideways are simulated in order to be analyzed and modified. literature review is conducted to identify existing research studies and publications related to the topic in order to identify gaps in the research and highlight areas that need further investigation. So, the innovative concepts and approaches of future research works are suggested in order to develop machining procedures and CNC machine tool structures using FEM methods.

Finite element simulation of machining operations is presented in section 2. Finite element simulation of machine tool elements is presented in section 3. The output results of the study and future research works are presented in section 4.

2. Finite element simulation of machining operations

The FEM uses mathematical models to understand and quantify the effects of actual conditions on process of part production using CNC machining operations. The finite element simulation is a valuable tool for simulating and optimizing machining operations [52]., FEM can improve the quality of finished parts, reduce tool wear and damage, and save time and resources in the manufacturing process using CNC machine tools by accurately modeling the physical behavior of metal cutting operations in virtual environments[53]. Cutting temperatures, cutting forces and energy consumption, chip formation process, deflection and deformation errors of thin-walled parts and tool wear rate during machining operations can be accurately simulated by using the FEA in order to be analysed and modified. As a result, the process of machining operations can be analyzed and developed using the FEA analysis methodologies.

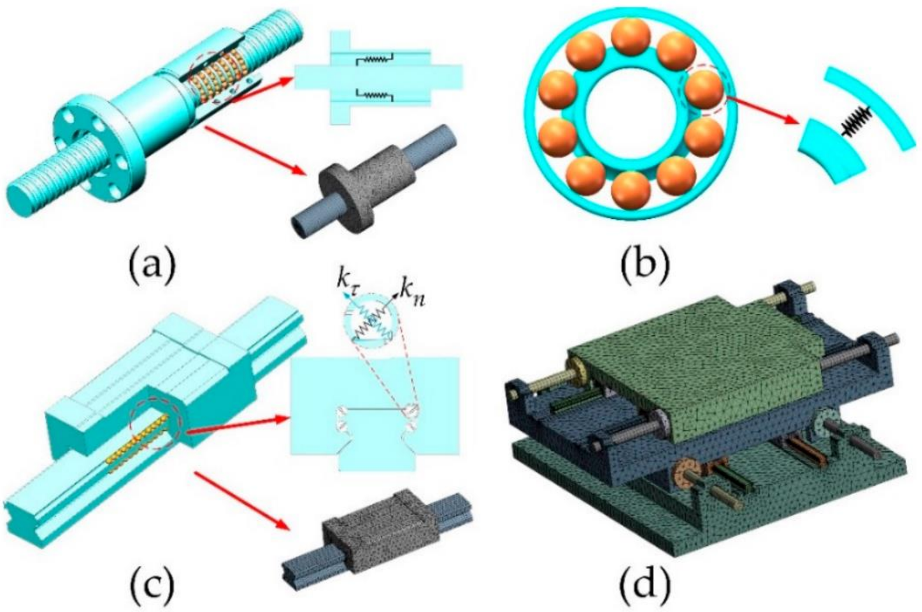

Figure 1. FEM model of twin ball screw worktable. (a) FEM model of ball screw and nut; (b) FEM model of angular contact bearing; (c) FEM model of linear guide; (d) FEM model of whole twin ball screw system [19].

2.1. Cutting temperature

Cutting temperature is a critical factor in CNC machine tool operations which can affect the cutting tool life and efficiency of machining operations. Controlling the cutting temperature is critical in CNC machine tool operations to ensure the efficient and reliable production of high-quality parts. Cutting temperature has a direct impact on tool wear. A higher temperature can lead to increased wear and deformation of the cutting tool, reducing its lifespan and increasing the need for tool replacement, which can result in production downtime and additional costs. The cutting temperature affects the surface finish of the machined part[54]. High temperatures can cause thermal damage to the surface, resulting in surface cracks, roughness, and residual stresses. Also, high cutting temperatures can cause the workpiece to expand, which can lead to dimensional inaccuracies and tolerance issues, leading to rejected parts.

Finite element simulation of cutting temperature in machining operations can provide valuable insights into the heat generation and transfer mechanisms during the cutting process. This information can be used to optimize the machining process parameters and improve the machined surface quality and cutting tool life[55]. An analysis of the thermoelectric connection and an empirical studies of the feed mechanism for CNC machine tools are offered to enhance the dynamic response of milling processes[56].To lessen the thermal inaccuracy in the X- and Z-directions during machining operations, digital temperature point optimization and experimental study for bi-rotary milling heads of five-axis CNC machine tools are explored[57]. Based on the temperatures of the moveable components, the FEM approach is utilized to compute the thermal displacement of the CNC horizontal lathe[58].In order to correct thermal error in machined components, a thermal error forecasting model for a CNC machine tool spindle system utilizing linear correlation is investigated[59]. To analyze the temperature distribution near the cutting tool, a novel approach of integrating traditional finite element machining simulations with computational fluid dynamic (CFD) model is proposed[60]. To estimate the impacts of cutting fluid on the temperature of the tool during cutting operations, a coupling technique integrating computational fluid dynamics and finite element method is used[61].A computational and experimental research is provided to evaluate convective heat transfer and related cutting heat transfer in single point turning operations[62]. WC-Co cutting tools are subjected to FEM analysis to lower in-service temperature [63].Using FEM and CFD, a multipoint cutting tool temperature study is carried out to reduce the cutting temperature during the chip creation process[64].In order to reduce thermal errors during machining operations, heavy-duty CNC machine tool thermal error monitoring technology employing the fem technique is created[65]. In order to increase the precision of the mill head, thermal characteristics study of the mill head of a five-axis CNC mill machine based on finite element approach is implemented[66].A virtual machining software is developed to analyze and minimize cutting temperatures throughout milling operations of difficult-to-cut items[27].Figure 2 depicts the surface temperature throughout the milling simulation of the titanium alloy Ti6Al4V [27].

So, the cutting temperature during machining operations can be accurately predicted using FEM simulation of chip formation process in order to minimize the cutting temperatures. So, cutting tool life and residual stress during machining operations can be increased in terms of accuracy as well as productivity enhancement of part production using CNC machining operations.

2.2. Cutting forces calculation

FEM of cutting forces in machining operations is a powerful tool for optimizing the machining process, reducing production costs, and improve product quality. By simulating the cutting forces, engineers can optimize tool design, cutting parameters, and material selection in order to achieve the desired results in process of machining operations. In order to precisely forecast the cutting forces during turning of stainless steel AISI 316L, the application of the FEM approach is presented [67].To precisely anticipate the cutting forces during turning operations, a numerical and experimental analysis of cutting forces in turning of Nimonic 80A superalloy is conducted [68].Figure 3 displays the cutting forces as determined by finite element analysis[68].

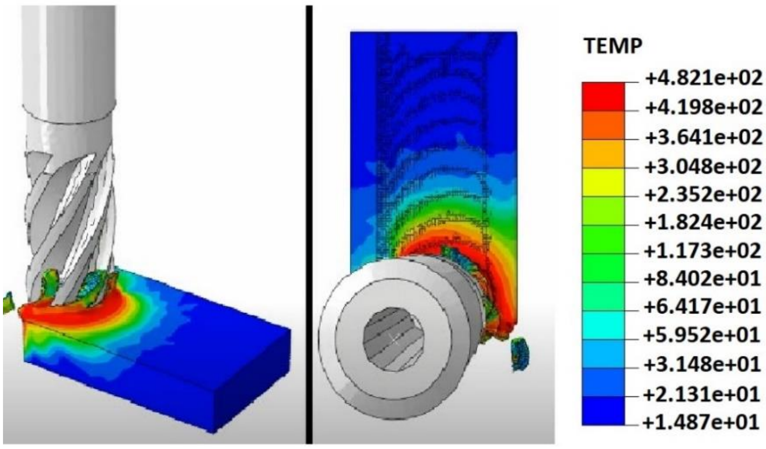

Figure 2. The titanium alloy Ti6Al4V's temperature field throughout FEM milling simulation [27].

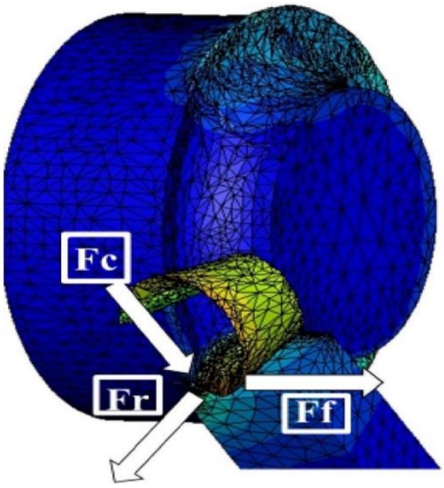

Figure 3. The predicted cutting forces by the finite element analysis[68].

To accurately predict the cutting forces encountered during the micro end milling of titanium alloy Ti-6Al-4V, a hybrid modelling technique for cutting force estimate is provided [69].To precisely compute the cutting forces during titanium alloy micro-turning, a mechanistic and finite element model for cutting force prediction is proposed[70]. In order to precisely estimate the stability limit and cutting forces throughout the chip formation process, the dynamic stability and cutting forces during the micro milling of Ti6Al4V are predicted utilizing FEM approach [71]. To precisely determine the cutting forces throughout machining processes, modelling of cutting conditions in micro end-milling is described[72].To precisely anticipate and reduce energy consumption during machining processes, cutting forces and power usage in turning of AISI 420 Martensitic Stainless Steel are simulated using FEM methodologies [73]. Therefore, an accurate estimation of cutting forces during machining operations can be obtained in terms of cutting tool paths and machining methodology modifications using FEM simulations.

2.3. Chip formation process

The process of chip formation in milling and turning operations occurs when the cutting tool removes material from the workpiece, resulting in the creation of chips or swarf. The chip formation process is a complex phenomenon that involves various factors such as cutting speed, feed rate, depth of cut, tool geometry, and material properties. The FEM simulation can provide insights into the chip formation process, such as the temperature distribution, the stress and strain fields, and the chip morphology. The simulation results can be used to optimize the cutting conditions, such as the cutting speed, feed rate, and depth of cut, to achieve better chip control, improve surface finish, and extend cutting tool life.

By considering the formation of the workpiece surface and any harm brought on by chips formed during the machining process, prediction of chip shape is an important step in machining process modifications[74]. The emerging chip generation process is modelled analytically and using FEM to increase the rate at which material is removed during machining operations[75]. To precisely anticipate the cutting force and chip shape, finite element modelling is conducted on the cutting mechanism of nano Mg/SiC metal matrix composites[76].Chip morphology at uncut chip thickness of (a) 0.1 μm; (b) 0.2 μm; (c) 0.5 μm; (d) 1 μm; and (e) 2 μm is shown in the figure 4.

In order to improve the surface quality of machined components, chip formation and surface integrity predictions are examined using FEM methodologies [77].In order to examine the impacts of cutting speed on chip properties, a simulated and experimental investigation of the generation of serrated chips for the hard milling process is provided[6]. Figure 5 compares the outcomes of simulations and experiments using serrated chips[6].

To examine the impact of feed rates and depth of cuts on the chip formation process, a FEM modelling and experimental examination of force and chip morphology on hot turning of Inconel 625 are provided[78]. Figure 6 depicts simulated chip development and force under hot and cool conditions.[78].

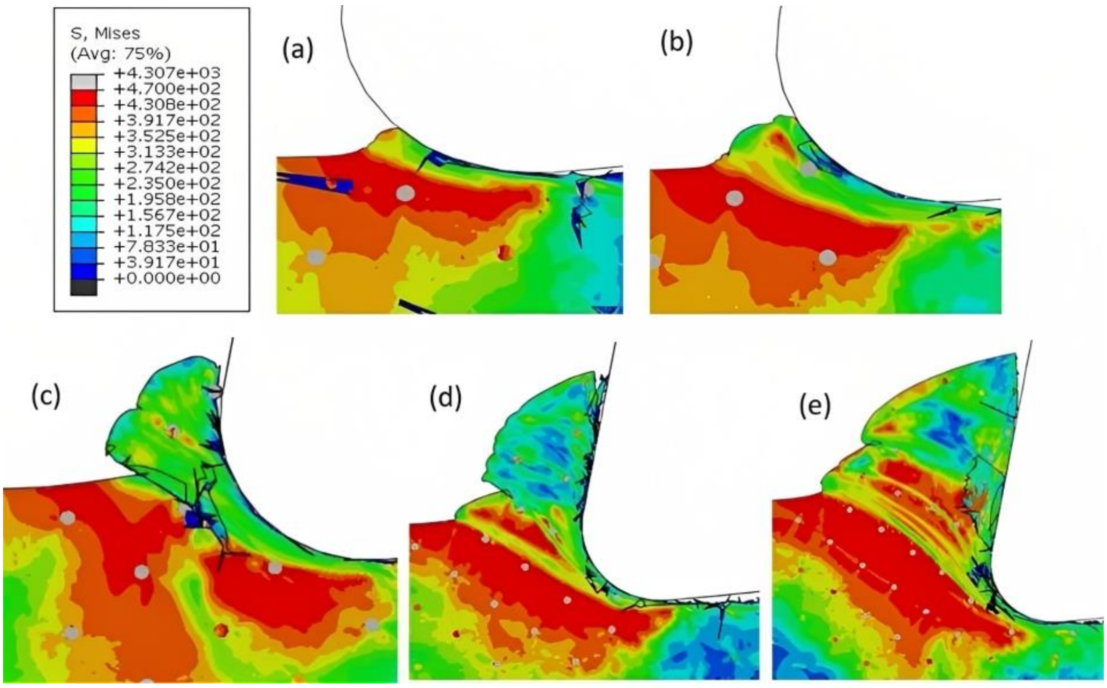

Figure 4. Chip morphology at uncut chip thickness of (a) 0.1 μm; (b) 0.2 μm; (c) 0.5 μm; (d) 1 μm; and (e) 2 μm[76].

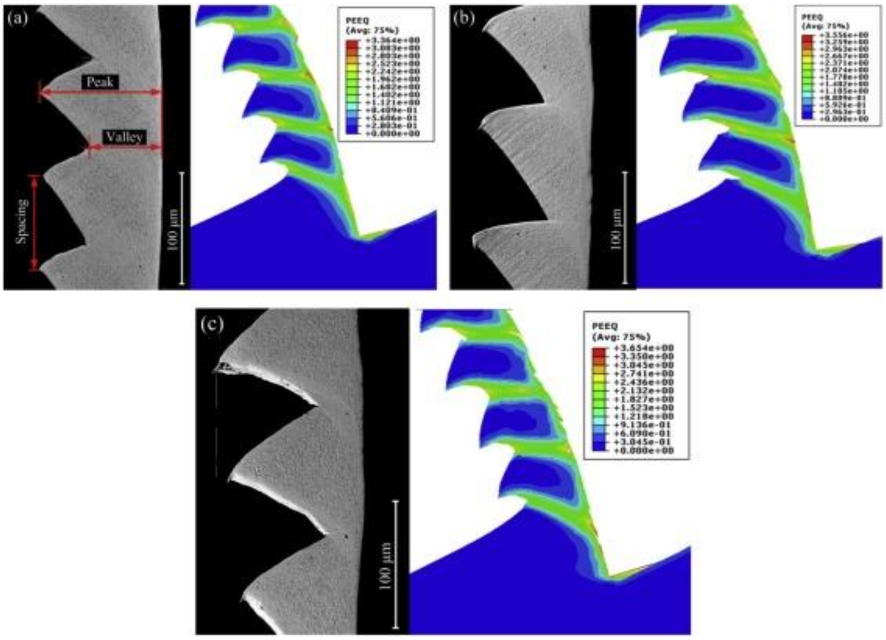

Figure 5. The outcomes of FEM simulations and experiments using serrated chips[6].

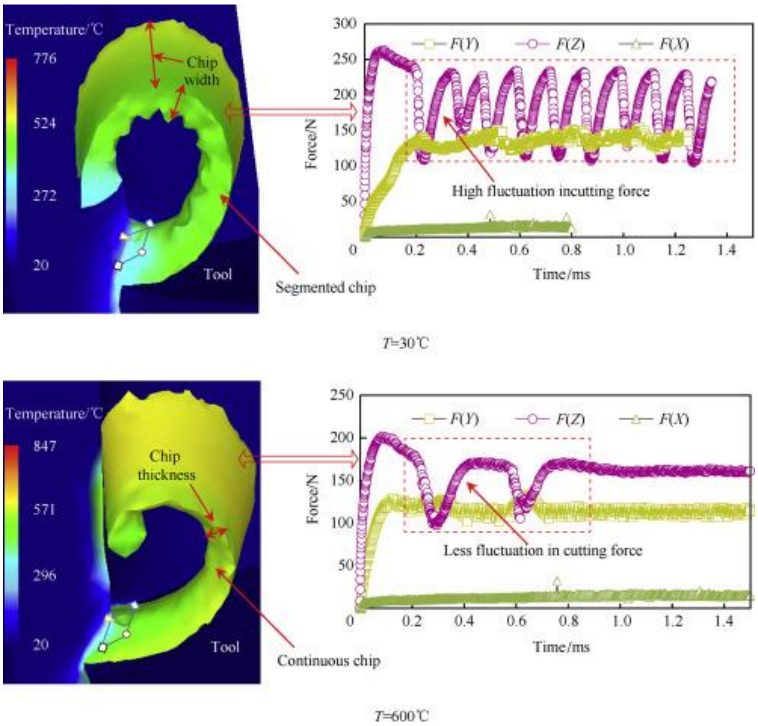

Figure 6. Simulated chip development and force under hot and cool conditions [78].

A FEM model of chip formation in orthogonal cutting in-situ TiB2/7050Al MMC is provided in order to accurately foresee the mechanisms of chip generation, involving plastic deformation, adiabatic shear, shearing slip, and crack development[79]. Figure 7 illustrates the results of a chip morphology study using experimental results (a, c) and finite element method (FEM) simulation results (b, d)[79].

In order to determine the chip morphologies of polymers from the real stress-strain curve, cutting force and chip formation are predicted from the true stress-strain relation [80].In order to illustrate the most current developments in the uses of FEM techniques in CNC machining processes, numerical approaches for the modelling of chip production are examined[81].To accelerate material removal rate during machining operations, a boundary condition for chip production in the cutting process of grey cast iron utilizing fem technique is created[82].As a consequence, chip morphologies, mechanisms of chip generation, prediction of chip shape and material removal rates during machining operations of different workpiece materials and machining strategies can be accurately precited and analyzed using FEM simulation.

2.4. Residual stress

Residual stresses are generated during machining operations due to the application of mechanical forces and thermal gradients during chip formation process. These stresses can have a significant impact on the performance and reliability of machined components in different working conditions. FEM is a powerful tool to predict and analyze residual stress in turning operations. By using FEM, engineers and researchers can optimize the cutting parameters and improve the quality of the machined parts.

In order to examine the relationships between the federate, depth of cut, and cutting speeds to the cutting conditions and residual stress in metal cutting of titanium alloys, 3D finite element studies on textured tools with various geometrical forms are provided[83].Figure 8 demonstrates the differences of von-Mises stresses for plain and textured tools with different depth[83].

To determine how the distribution of residual stress in the machined workpiece is affected by the microstructure of the material, a finite element simulation of residual stress in Ti-6Al-4V machining is provided[84].To measure and reduce residual stress throughout metal cutting processes, a review of machining-generated residual stress is given[34]. A virtual machining method is created to reduce deflection inaccuracy and residual stress in five-axis CNC milling operations of turbine blades [26].Analyses of machining-induced residual stresses in machining of titanium and nickel-based alloys using experiments and finite element simulations are offered in order to assess and enhance the fatigue performance of nickel and titanium alloy products[85].Finite element modelling and experimental study on the residual stress-related homogeneous component deformation are presented in order to minimize the deformation error caused by residual stress throughout milling operations[86].In order to reduce residual stresses caused by machining in IN718 nickel-based alloy, numerical calculations have been performed [87].Therefore, fatigue life of produced parts using CNC machine tools can be extended by analyzing and minimizing residual stress using FEM simulations in terms of accuracy and reliability enhancement of part production using CNC machining operations.

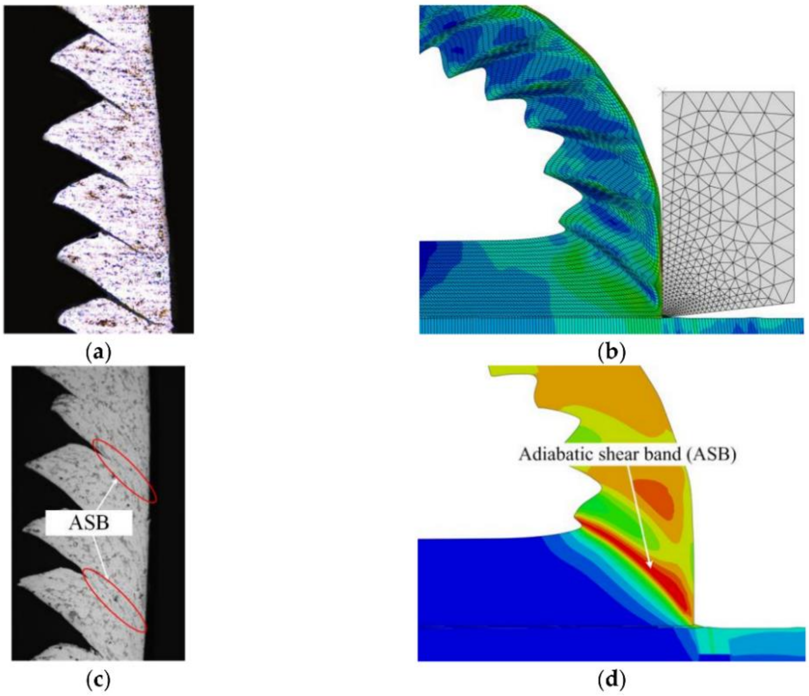

Figure 7. The results of a chip morphology study using experimental results (a, c) and finite element method (FEM) simulation results (b, d)[79].

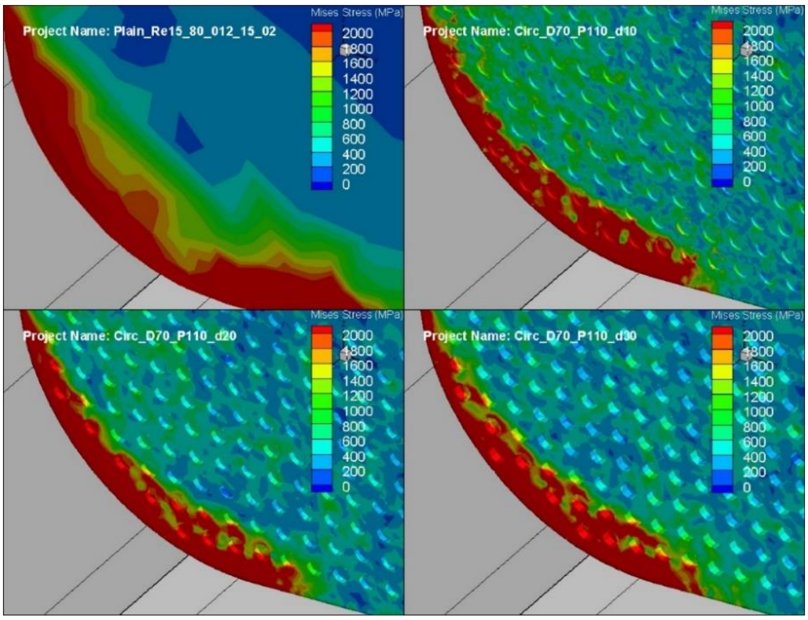

Figure 8. The differences of von-Mises stresses for plain and textured tools with different depth[83].

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2.5. Deflection and deformation errors of thin-walled parts

During machining operations, thin-walled parts can be subject to deflection and deformation errors, which can negatively affect the accuracy and quality of the finished product. Deflection and deformation are often caused by the cutting forces and thermal expansion that occur during machining.The surface inaccuracy in the machining of thin-wall workpieces is greatly influenced by temperature and force-induced deflection. It is important to carefully consider the design and manufacturing processes of thin-walled parts to minimize deflection and deformation errors. Consideration of physical parameters, such as material characteristics, tool geometry, and FEA-based modelling can all be used to properly anticipate deflection and instability during machining operations of thin walled parts[88].To calculate the surface positioning error of the workpiece, the rigid-flex model is examined and the finite element prediction approach in the field of machining error of thin-walled components is implemented[89, 90].To precisely anticipate the deformations of machined thin walled components, a machining error prediction system based on the force-deformation coupling relationship is proposed[91].In order to forecast the surface errors that will be left on the final component, a surface form error prediction method for thin-walled parts using five axes flank milling is described[92]. In order to increase the precision of machined components utilizing micro-milling operations, deflection modelling of micro-milling Inconel 718 thin-walled parts using the FEM approach is described[93].Virtual machining techniques is created to decrease the deflection error in five axis machining processes of impeller blades [29]. To compensate deformation errors in five-axis CNC milling operations of turbine blades, application of virtual machining system is developed [94].To reduce milling deformation of micro thin-walled components, deformation theory and mechanism for milling titanium alloy micro thin wall with mixed boundaries are examined[95]. Results of DEFORM-3D finite element simulation is shown in the figure 9[95].

Thus, the accuracy of final products can be increased using the FEM simulation of deflection errors during machining operations of flexible parts. The predicted deflection errors can be minimized using the optimized machining parameters in order to enhance accuracy of machined components using CNC machine tools. Also, compensation methodologies can be applied to the predicted deflection errors in order to enhance accuracy of produced parts using machining operations.

2.6. Tool wear

Tool wear is a common phenomenon in machining operations, where the cutting tool gradually loses its sharpness due to various factors such as friction, heat, and chemical reactions. The gradual loss of sharpness can cause several issues in the machining process, including reduced accuracy, poor surface finish, and increased tool replacement costs. To reduce tool wear throughout end milling, finite element simulation and experimental research on the cutting action in vibration-assisted micro-milling are given[96].In order to extend the life of the cutting tool throughout the chip creation process, a finite element modelling of high speed micro milling with tool run-out is provided[97].To reduce tool wear during machining operations, the mechanism for wear rate suppression in non-resonant vibration-assisted micro milling is examined[98].In order to forecast tool wear under both MWF and LN2 cooling circumstances, numerical modelling of tool wear in drilling Inconel 718 under flood and cryogenic cooling settings is provided[99]. Figure 10 illustrates simulated (top) and actual (bottom) tool wear during machining processes [99].

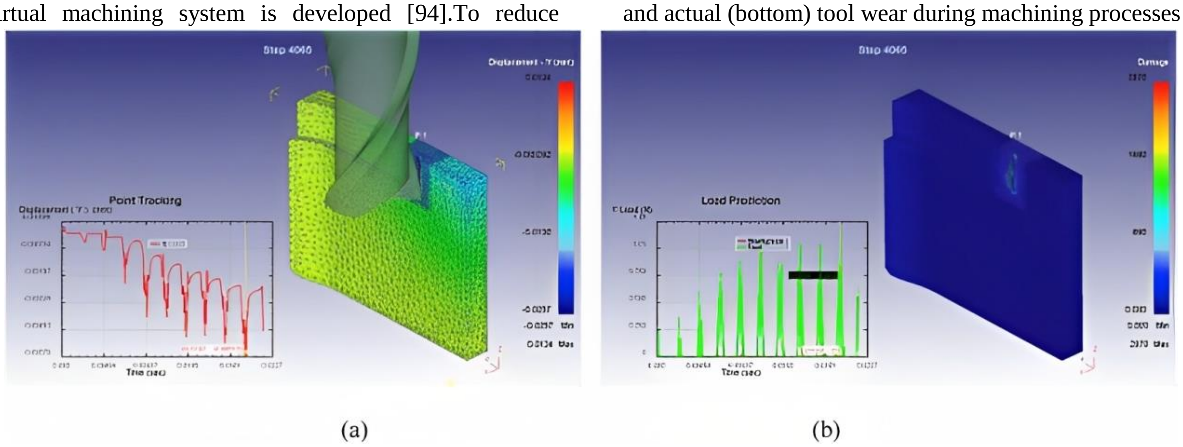

Figure 9. Results of DEFORM-3D finite element simulation[95].

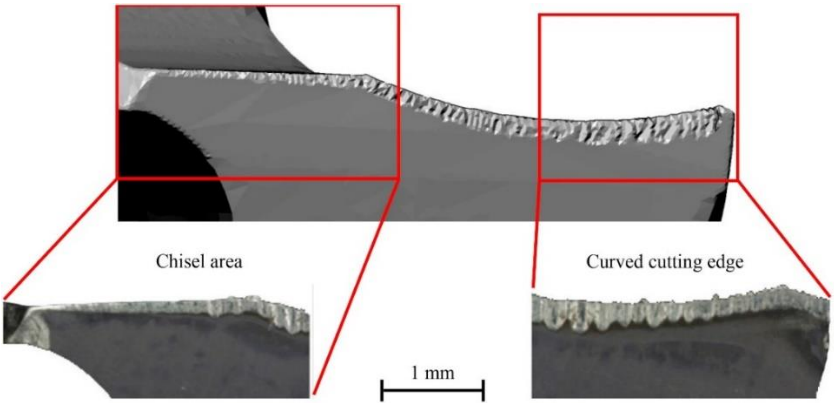

Figure 10. Simulated (top) and actual (bottom) tool wear during machining processes [99].

To extend the working life of cutting tools used in orthogonal cutting operations, a study of tool wear estimates utilizing theoretical analysis and numerical simulation methods is offered[100].To optimize the efficiency of the component manufacturing process by limiting tool wear and improving surface quality, the effects of tool wear on plastic flow and deformed material in turning operations of Ti-6Al-4V [101].Figure 11 displays the strain and strain rate distribution for various tool wear conditions.

A 3D finite element simulation approach is used to forecast and enhance tool wear in longitudinal-torsional ultrasonic-assisted milling processes[102].To increase cutting tool life in machining processes, a mixed experimental and simulation technique to evaluating the calibration of tool wear rate models is proposed[103]. In order to precisely estimate and minimize tool wear in machining processes, a research on tool wear in ultrasonic vibration-assisted milling of C/SiC composites is provided [104].To examine the impact of ultrasonic vibrations on the tool wear rate during machining operations, experiments and finite element simulation of ultrasonic aided drilling are provided[105]. As a consequence, cutting tool life during machining operations of different materials and different methods of chip formation can be accurately predicted using the FEM simulation in terms of productivity enhancement of part manufacturing using CNC machine tools.

3. Finite element simulation of machine tool elements

Finite element simulation is a powerful tool for analyzing the behavior of machine tool elements in virtual environments. It allows designers to test and optimize the designing process of machine tool elements under a range of conditions.[106].Different elements of machine tool such as machine tool bed, ball screw, spindle and guideways are simulated by using the finite element methods to increase the performances of elements such as mechanical properties in actual working conditions. Thus, accuracy as well as reliability of designed machine tool elements can be enhanced using FEM analysis and modification

3.1. Machine tool bed

Machine tool beds are responsible for providing a stable and rigid platform for the cutting process to take place, and any deformation or vibration in the bed can lead to poor surface finish, reduced accuracy, and shortened tool life. Finite element simulation can provide a powerful tool for designing and optimizing machine tool beds for maximum stiffness, stability, and accuracy. In order to understand how a machine tool's vibration mechanisms work, the bed structure should be examined as a key component in the machine tool structure [107].To determine the machine tool's static stiffness under cutting loads, the deformation structure of a milling machine subjected to self-weight loading circumstances is presented[108].Figure 12 depicts the milling machine's distortion shape under conditions of self-weight pressure [108].

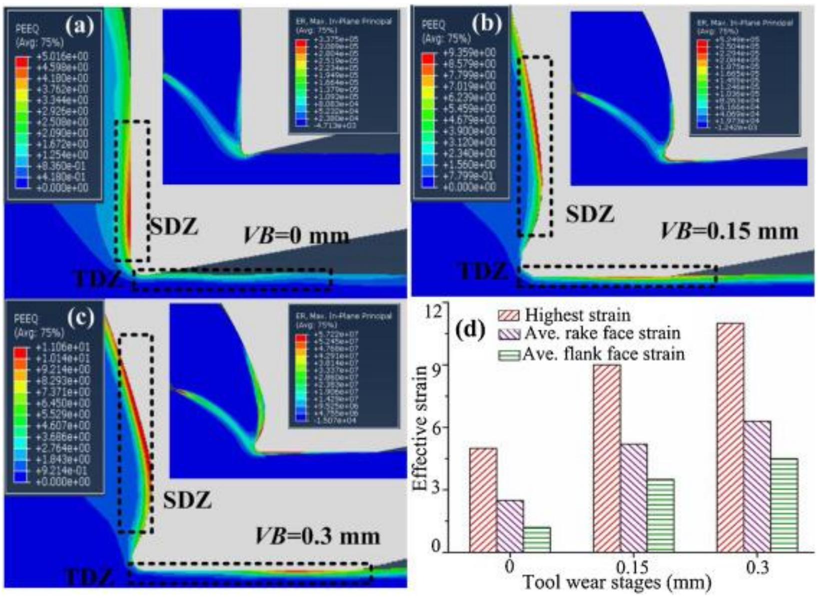

Figure 11. The strain and strain rate distribution for various tool wear conditions.[101].

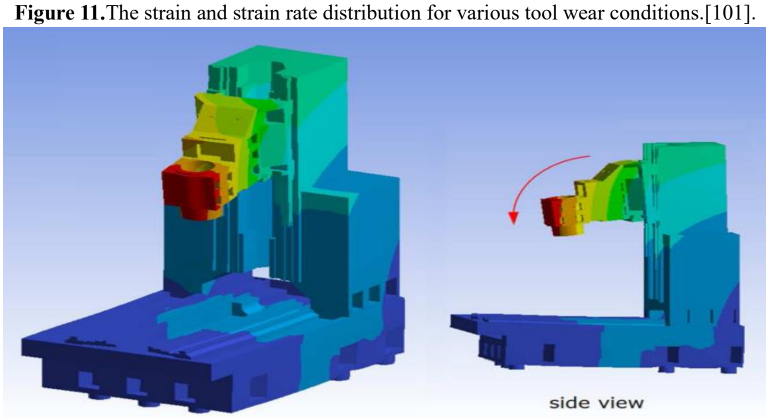

Figure 12. Deformation shape of milling machine under self-weight loading conditions[108].

In order to produce a steel-reinforced epoxy granite machine tool column with higher structural damping, equivalent or higher static stiffness, an easy and environmentally friendly manufacturing process, and all of these characteristics, a structural investigation using finite element analysis is presented[109].To calculate and reduce the impacts of vibrations to the accuracy of machining operations, rigid finite element technique is used to model composite steel-polymer concrete machine tool frames[110]. Figure 13 compares the specified vibration mode forms for the machine tool body between both the RigFEM, FEM model, and experimental data[110].

In order to forecast the strength behaviour of laser powder bed fusion Ti-6Al-4V components, including softening beyond the uniform elongation limit during machining processes, mechanical parameters of the parts are studied using finite element models[111]. In order to assess and reduce the thermal deformation error during machining operations, thermal performance modelling and simulation of machine tool beds using FEM analysis is provided[112].Dynamic characteristics analysis and finite element modelling of the steel-bfpc machine tool joint surface are carried out to enhance the vibrant performance of the machine tool bed throughout machining operations [113].A hybrid polymer cement bed for a high-speed CNC milling machine is proposed in order to evaluate and lessen the effects of vibrations on the quality of machined components [114]. So, materials, structural designing and dynamics stabilities of CNC machine tool beds can be analyzed and modified using FEM simulation in order to develop the CNC machine tool structures.

3.2. Ball screw

A ball screw is a mechanical device used to convert rotary motion into linear motion. It consists of a threaded shaft, called the screw, and a nut that contains a series of balls that run in the thread. As the screw rotates, the balls move along the thread, causing the nut to move linearly. Ball screws are widely used in machine tools, robotics, and other applications where precise linear motion is required. The FEM analysis can be used to predict several important characteristics of the ball screw, such as its stiffness, strength, and fatigue life. It can also be used to optimize the design of the screw and nut, for example, by varying the thread profile or ball diameter to improve its performance[115].To improve the performance of the ball screw systems under real-world operating situations, finite element modelling of ball screw feed drive systems is offered [116]. To determine the contact stress in a ball screw and quantify the deformation error during translational motion, a finite element analysis model is provided[117].Figure 14 displays the comparable stress (MPa) outcomes of the contact theory-based model (shaft)[117].

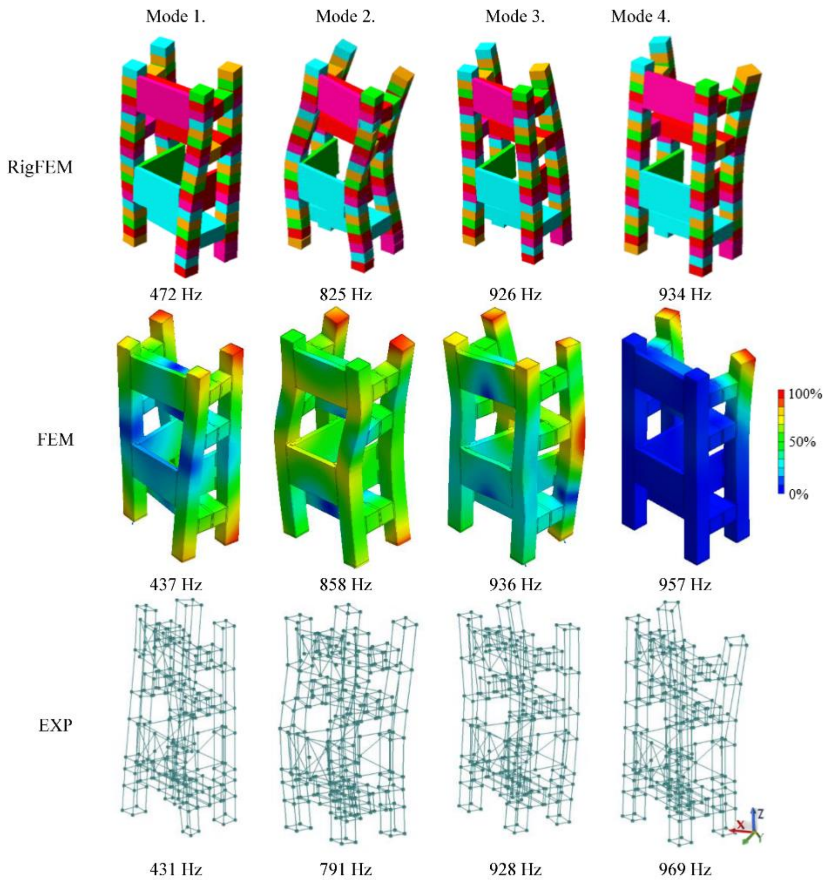

Figure 13. Comparison of the selected mode shapes between the RigFEM, FEM model, and the experimental results for the machine tool body[110].

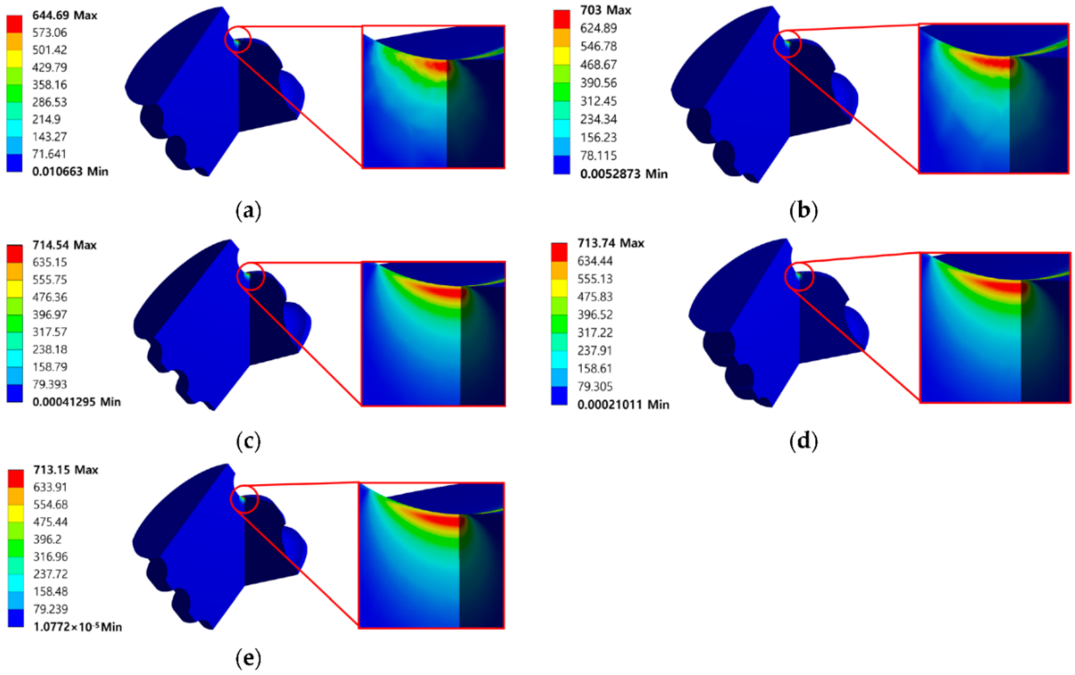

Figure 14. Equivalent stress (MPa) results of contact theory based model (shaft)[117].

Dynamic analysis and experiment investigation on a twin ball screw feed system taking joint stiffness into consideration are offered to increase accuracy in CNC machining operations[19].

An experimental and theoretical assessment of the stress distribution in a ball-screw system is offered in order to prolong the useful life of the ball-screw systems[118].The rate of warming and thermal error of the lead screw under operating circumstances are reliably predicted using the thermal error modelling approach for the ball screw feed system of CNC machine tools[119]. To reduce the impact of machining disturbances on the precision of machined products, finite element analytical model of the ball screws linear guide feed unit is used[120]. Positioning error modelling for ball screw systems using the FEM techniques is presented in order to be compensated in terms of accuracy enhancement of machined parts[121].To improve positioning and machining precision during machining operations, temperature modelling and thermodynamic equilibrium analysis of the ball screw feed drive system under various operating circumstances are provided[122].The axial static stiffness of a double-nut ball screw with heavy load and high precision is offered by theoretical calculation and computational methods in order to increase the accuracy and durability of double-nut ball screw systems[123].

Thus, performance of the ball screw systems can be analyzed and modified using FEM simulation of ball screw systems in order to enhance positioning and machining precision during CNC machining operations. Moreover, the dynamic behavior of the screw and nut under different operating conditions, such as varying loads and speeds can be simulated and analyzed using the FEM methods.

3.3. Spindle and guideway-slider

The most important part of ultra-high-speed machining equipment is a motorized spindle, which unites a motor shaft and the main axis of the machine tool without the use of a belt or gear transmission. Precision of CNC machine tool is under influence of motorized spindle where thermos-mechanicalloadsduring machining operations can impact on the motorized spindle's accuracy. The deformation error of a motorized spindle is caused by the interaction of these two types of loads with the machining operation[124].

The finite element model for the simulation of spindles includes the spindle shaft, bearings, and any other relevant components such as the motor or pulley. The model is then subjected to various loads and boundary conditions, such as axial and radial forces, torque, and rotational speed. The simulation can be used to analyze the stress and deformation of the spindle under different loading conditions, as well as to optimize the design to improve performance and reduce the risk of failure.

The finite element model for guideway-sliders includes the guideway, slider, and any other relevant components such as the bearings or lubrication system. The model is then subjected to various loads and boundary conditions, such as the weight of the slider and the forces exerted on it during motion. The simulation can be used to analyze the friction and wear of the guideway and slider, as well as to optimize the design to improve performance and reduce the risk of failure.

The static rigidity design of a vertical lathe with a steel-polymer concrete frame is investigated in order to study the impact of cutting loads on the static stiffness of the machine tool platform[125]. Figure 15 displays Machine tool component Finite Element Models[125].

To forecast the dynamic behaviour at the spindle tool tip owing to the impacts of machining vibration in the chip generation process, an analysis of the machining stability of a milling machine is provided, taking into account the influence of the machine frame structure and spindle bearings[126].In order to predict the thermal permanent deformation of the spindle during machining operations, the thermal characteristics of a spindle system are simulated using the finite element approach[127].To reduce the influence of thermal distortion on the precision of machined components, a simulation of the thermal behaviour of a CNC machine tool spindle is provided [128].Figure 16 depicts the spindle's thermal permanent deformation during the thermal balance stage[128].

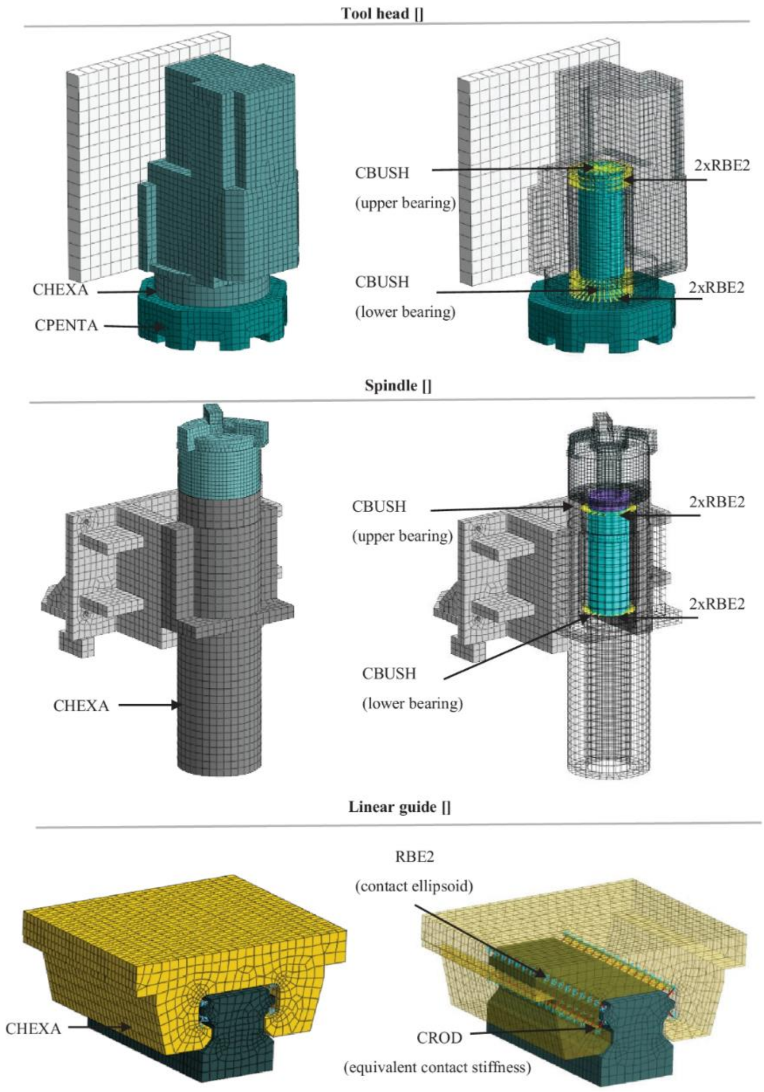

Figure 15. Machine tool component Finite Element Models[125].

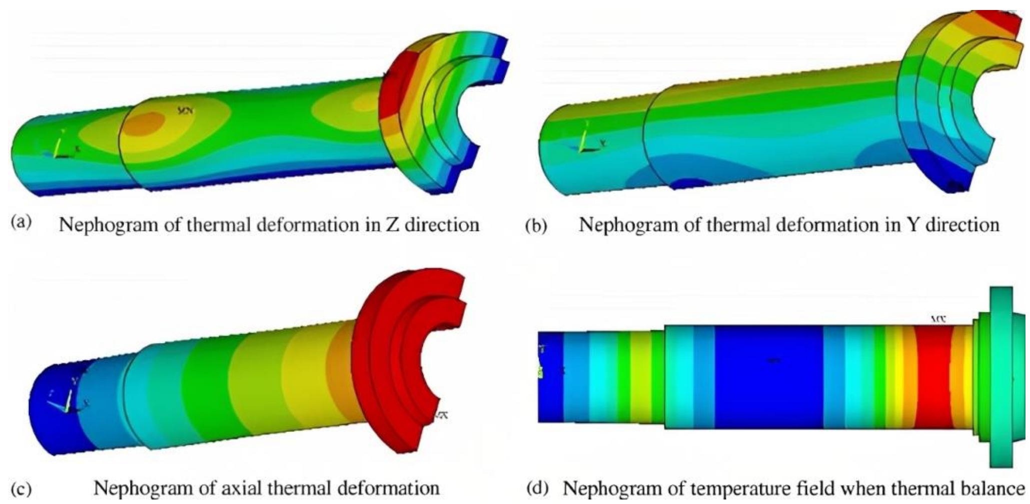

Figure 16. The spindle's thermal permanent deformation during the thermal balance stage[128].

Finite element analysis is used to examine how different orientation speeds affect the temperature distribution, temperature growth, and thermal displacement of the spindle component[129].The geometric inaccuracies of linear frames and their effects on joint kinematic error are studied using FEM techniques in order to assess and minimize the volumetric defects in machine tools[130].To improve the static stiffness and guiding precision during machining processes, a finite element study of the static properties of a hydrostatic guideway is provided[131].The machining durability of a milling machine utilizing hybrid guideway systems is demonstrated, and the influence of vibration on the accuracy of CNC machining operations is minimized, through using finite element method[132]. Using the FEM simulation, different orientation speeds, dynamic behaviour at the spindle tool tip, thermal loads, vibrations and effects of harmonic forces on the spindle and guideway-slider can be accuratelypredicted in order to be analyzed in terms of accuracy as well as productivity enhancement of part production. Overall, finite element simulation is a powerful tool for analyzing and optimizing the performance of mechanical systems, including spindles and guideway-sliders. It can help engineers to identify potential design problems, optimize the performance of the system, and reduce the risk of failure or downtime.

4. Summery of the study

The paper reviews the analysis and customization of CNC machine tool operations and structures using finite element methods. In order to demonstrate the capabilities of FEM simulation in CNC machining modification, applications of the FEM methods in simulation of cutting temperatures, cutting forces and energy consumption, chip formation, deflection and deformation errors of thin walled components, and tool wear rate during machining processes, are reviewed from recent published papers. Also, finite element approaches are used to enhance the performances of different machine tool components under real-world operating situations. In order to evaluate and modify different machine tool components, such as the machine tool bed, ball screw, spindle, and guideways, they are simulated using FEM methods.

5. Conclusion and future research work directions

To create components with the correct size, shape, and surface polish, machine tools are employed. Stiffness, structural damping, and long-term dimensional stability of the machine tool structures all have an impact on machining precision. A review of recent advancements is provided with the goal of determining how to move forward in the development of a numerical approach used to represent CNC machining processes. To demonstrate the capabilities of FEM simulation in CNC machining modification, applications of the FEM methods in simulation of cutting temperatures, cutting forces and energy consumption, chip formation, deflection and deformation errors of thin-walled components, and tool wear rate during machining processes are reviewed. Additionally, finite element methods are used to model various machine tool components such as the bed, ball screw, spindle, and guideways in order to enhance the performances of various machine tool elements such as mechanical properties in real-world working scenarios. Thus, the development of the machining operations process using FEA analysis methodologies is made possible by the assessment of current achievements in the published papers.There are several areas where FEM can be applied to enhance CNC machine tool operations and structures. One of the main areas is the optimization of machine tool structures to increase their stiffness, reduce their weight, and improve their dynamic response[133]. This can be achieved by using FEM to simulate the behavior of the machine under different loading conditions and identify the optimal design parameters that meet the desired performance criteria.

Deviations of a workpiece, fixtures and clamping systemsduringCNC machining operations can be accurately predicted using the FEM methods. Surface integrity of new superalloys, difficult to cut materials as well as composite structures, can be accurately predicted in order to be enhanced using the FEM techniques. The effects of new cutting tool angles and shapes to the cutting tool life and tool wear can be predicted in order to develop the cutting tool inserts for the different machining operations. New alloys of cutting tools can be analysed under the chip formation process in order to enhance the cutting tool life and performances in CNC machining operations. The effects of coolant to the cutting forces and temperatures can be simulated using the FEM in order to be enhanced in terms of efficiency enhancement of machining operations. Residual stress and strain distribution during machining operations of accurate parts such as turbine blades and blisks of jet engines can be accurately predicted in order to be minimized.In order to reduce impact force and transmission errors during cutting operations in the moving axis of CNC machine tools, predictions can be made.The influences of vibrations and chatter during machining operations can be simulated in order to be minimized. To enhance the productivity in CNC machine tool operations and structures, optimization methods can be applied to the machining parameters and machine tool elements. To decrease the energy usage in the machining operations, the cutting forces can be predicted and minimized in order to provide advanced green manufacturing in process of part production using CNC machining operations. FEM can be used to simulate the thermal behavior of the machine tool and optimize its design to minimize the thermal distortion effects. FEM method can also focus on developing more advanced simulation models that can accurately capture the complex behavior of the machines under different loading and environmental conditions. This can be achieved by combining FEM with other modeling techniques such as computational fluid dynamics (CFD), multi-physics simulations, and artificial intelligence (AI) algorithms. Furthermore, machine learning algorithms can be trained on large datasets of machine tool performance data to identify patterns and correlations that might not be apparent through traditional modeling approaches. This could lead to new insights into the behavior of machine tools and help optimize their performance. Finally, there is a need for research on the design and optimization of machine tool structures to improve their performance and reduce their environmental impact. This could involve the use of new materials or the development of novel design approaches that take into account factors such as vibration damping and thermal management. These are a few ideas for possible research works in the future which can enhance the production process using CNC machine tool operations.

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