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A Review in machining-induced residual stress

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Abstract

Due to friction, chip forming, and the induced heat in the cutting area, produced parts by using machining operations have residual stress. Residual stresses caused by machining processes have a major effect on the fatigue life of machined components, which can shorten their service life. In order to increase the performance of machined parts in real-world applications, such as fatigue life, corrosion resistance, and component distortion, residual stress should be investigated and minimized. As a result, predicting and controlling residual stresses caused by machining operations is important in terms of quality enhancement of machined parts. This paper reviews the recent achievements in the machining-induced residual stress in order to be analyzed and decreased. Different methods of the residual stress measurement Destructive Methods, Semi-Destructive Methods and Non-Destructive Test (NDT) Methods are reviewed and compared in order to be developed. In order to minimize residual stress in machined parts, the study examines the effects of machining process parameters, high-speed machining conditions, coolant, cutting tool wear, edges, and radius on residual stress. Analytical and semi-analytical modeling, numerical and FEM simulation techniques of residual stress are reviewed to include advanced methods of residual stress modeling methodology to predict residual stress in machined components. Residual stress in various alloys such as AL alloys, biomedical implant materials, hard to cut materials such as nickel-based alloys, Titanium Based Alloys, Inconel Based Alloys, and stainless-steel alloys is investigated in order to provide efficient residual stress minimization methods in machined components. It has been realized that evaluating and analyzing recent advances in published papers will contribute to develop the research field.

Keywords: Residual Stress; Machining Operations

1. Introduction

Casting, welding, machining, molding, shaping and plastic deformation during bending and rolling all cause residual stress in manufactured products. Residual stresses can appear in any mechanical system during plastic deformation for a number of reasons. These may include temperature differences in the material or changes in its composition (phase change). Residual stresses in machining operations are determined by the magnitude of the cutting forces as well as thermal stresses induced by the produced heat during the material cutting process. By causing plastic deformation in the components, mechanical processes introduce residual stresses into the body. The degree to which residual stresses are incorporated into the material can be defined as near surface (less than 1 mm from the free surface) or deep into the bulk (through thickness). Figure 1 illustrates a schematic diagram of non-uniform plastic deformation and residual stress formation during the turning process. [1].

In-homogenous plastic deformation caused by a mechanical and thermal load associated with the machining process may cause residual stresses. The applied mechanical load can produce both tensile and compressive residual stresses, while the thermal stress on the surface layer can only produce tensile residual stress [2].

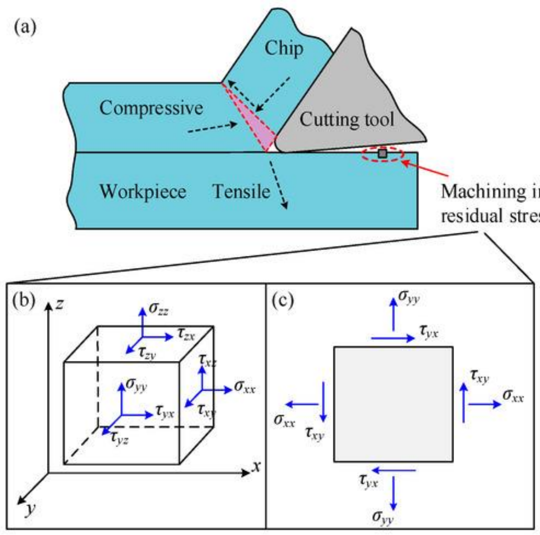


Figure 1. Generation of the Residual stress during machining, (b) space stress state, and (c) plane stress state [1].

The relation between the mechanical as well as thermal phenomena in generation of residual stress during machining operations is shown in the figure 2 [3]. As is presented after thermal expansion and phase transformation during chip formation process in machining operations, heterogeneous plastic deformation is created which can produce residual stress in the machined components.

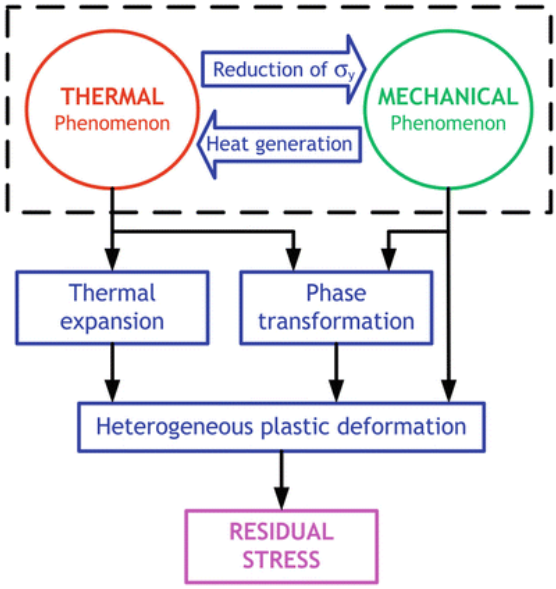


Figure 2. The relation between the mechanical as well as thermal phenomena in generation of residual stress [3].

The residual stresses can decrease the mechanical performance and even lead to premature failure of produced parts. When the magnitudes of residual stresses surpass the ultimate strength and fatigue, they are known to cause various engineering problems such as distortions, cracks, or delamination. The possibility of deformation in parts after machining operations or during working conditions due to machining residual stresses is one of the challenges of precision machining. In the performance of machined components and structures, residual stresses play an important role in fatigue life, corrosion resistance and partial distortion. In order to increase the performance of machined parts in real-world applications, such as fatigue life, corrosion resistance, and component distortion, residual stress should be investigated and minimized. As a consequence, in terms of improving the quality of machined components, predicting and managing residual stresses induced by machining operations is important.

To improve the efficiency of high-sensitivity components like turbine blades and jet engine blisks, the quantity and distribution model of residual stresses during machining operations is analyzed. As a result, residual stress should be investigated and reduced in order to improve the efficiency and durability of manufactured components. A new means of detecting, predicting, and controlling residual stress after chip-forming machining operations can be investigated in order to assess the stress–strain condition in various materials [4]. In order to provide advanced methods of the residual stress simulation, the benefits and limitations of various residual stress simulation approaches are addressed when it comes to modeling machining-induced residual stresses [5].

To analyze and modify the machining operations in virtual environments, virtual machining systems and applications are presented by Soori et al. [6-10]. To analyze the mechanical behavior of materials in cutting operation as well as Friction Stir Welding (FSW) operations, recent development in research works are reviewed by Soori and Asamel [11,12]. Applications of the Computer Aided Process Planning (CAPP) in the manufacturing systems is reviewed by Soori and Asamel [13]. To minimize the residual stress and deflection error in five axis milling operations of turbine blades, advanced virtual machining system is proposed by Soori and Asmael [14]. To minimize the deflection error in five axis milling operations of impeller blades, Soori and Asmael [15] developed virtual machining systems. To analyze and modify the applications of the Virtual manufacturing systems in development process of part production, virtual product development is studied by Soori [16]. To minimize residual stress and deflection error in five-axis CNC milling operations of turbine blades, application of virtual machining system is developed by Soori and Asmael [17]. To analyze and minimize cutting temperatures during milling operations of difficult to cut materials, application of virtual machining system is developed by Soori and Asmael [18].

To develop the decision support systems in the data warehouse management, advances in web-based decision support systems is studied by Dastres and Soori [19]. To develop the applications of the artificial neural networks in different areas such as risk analysis systems, drone control, welding quality analysis and computer quality analysis, a review in recent development and applications of the systems is presented by Dastres and Soori [20]. Applications of the information communication technology in the environmental protection is presented by Dastres and Soori [21] in order to decrease the effects of technology development to the natural disaster. A review of Radio Frequency Identification (RFID) based wireless manufacturing systems is presented by Dastres et al. [22] to increase efficiency of energy consumption, quality and transparency of data across the supply chain and accuracy and reliability during part prodcution process. To increase surface quality during five-axis milling operations of turbine blades, Soori et al. [23] presented advanced virtual machining system. In order to analyze and modify the parameter optimization process of machining operations, a review of the recent development from the published papers is presented by Soori and Asmael [24].

In order to enhance the functional performance of machined parts in actual working conditions, a study of surface integrity in machining and its effect on functional performance and life of machined products is discussed [25]. Modeling of machining-induced residual stresses is discussed and summarized to explain and analyze the advantages and disadvantages of each model in the residual stress simulation [5]. A analysis of grinding-induced residual stresses in metallic materials is provided in order to evaluate and reduce residual stress during machining operations [26]. To assess and reduce residual stress in machined components, the paper evaluation of residual stresses after Irregular Interrupted Machining operations is presented. [27].

In order to analyze and decrease the residual stress in the machined parts, the measurement methods as Non-destructive Testing (NDT), Destructive methods and Semi-destructive methods are implemented. In order to develop the measurement methods of residual stress in the machined parts, review of residual stress measurement methods is presented [28,29]. Non-destructive methods measure the factors affecting the relationship between residual stresses and the crystalline properties of materials. The developed method is for measuring the diffraction frequency of high-frequency electromagnetic radiation by comparing the distance of the atomic lattice in the altered state to the non-stress state [30]. Acoustic emission, X-Ray Diffraction (XRD) analysis and ultrasonic waves are among the most commonly used Non-destructive Testing (NDT) techniques for determining stresses, voids, and defects in a variety of components [31]. Destructive methods cause large and irreversible changes in the structure which is not possible to reuse the test sample [32]. Thus, either a spare part must be used to replace the specimen in the structure or an accurate physical model must be used as a laboratory specimen [33,34]. In the Semi-destructive methods, the residual stress in the sample part is measured by using the strain release methodology while only a small part of the material is harvested and the whole structure remains intact [35].

The choice of any of these methods depends on the information required and the nature of the sample being tested. The depth or degree of penetration of the measurement (on the surface or in the direction of depth), the longitudinal scale of the required information as well as the geometry and location of the sample are also factors involved in the choice of method [36].

2. Effects of Machining Process Parameters

The machining parameters as well as the material of the workpiece influence the created residual stress in machined parts. To analyze and minimize the residual stress during machining operations, machining process parameters such as spindle speed, depth of cut, feed rate and material removal rate are discussed in different research works. The influence of each parameter can be studied in order to decrease the generated residual stress in the machined parts. Residual stresses in the machined parts are increased as feed rate increases and cutting speed is reduced [37]. The obtained results as shown in the figures 3 and 4 [38,39].

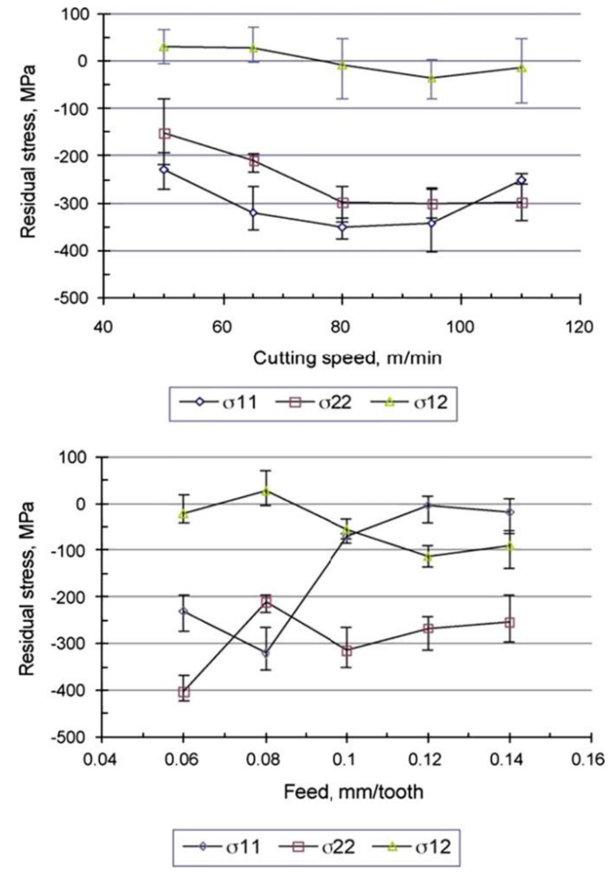


Figure 3. The effects of cutting speed and feed rate to the residual stress in end milling operations of Ti-64 with coated carbide tools at V=50–110 m/min, f=0.06–0.14 mm/tooth [38].

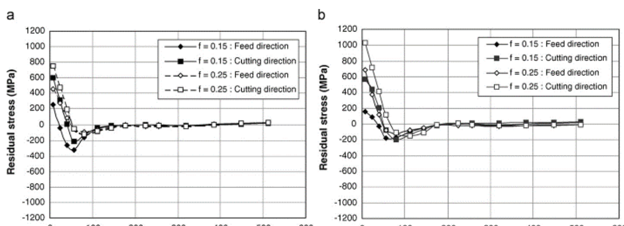


Figure 4. The measured residual stress in (a) new and (b) worn tools during turning operations of IN-718 at V¼40 m/min, f¼0.15–0.25 mm/rev, DoC¼0.25 mm [39].

The influence of process parameters on residual stress of machined parts in turning operations is examined, with the aim of assessing and reducing residual tress in turning operations [40]. To examine and reduce residual stress during machining operations, the effects of process parameters on residual stress and crystal size after microlaser-assisted machining of silicon components are investigated [41]. To improve the quality of machined parts by reducing residual stress, the influence of machining parameters and cutting tool parameters on residual stress are investigated [42].

To evaluate and minimize residual stress in machined parts, numerical analysis into the influence of machining parameters such as feed rate and cutting speed on residual stresses in orthogonal cutting operations is conducted [43]. The optimization of machining and stiffness parameters for residual stress minimization in ultrasonic assisted turning of 4340 hardened steel is proposed to fully define the thermo-mechanical mechanism responsible for residual stress generation during machining operations. [44]. In order to attain the desired residual stress distribution in machined components, the influence of cutting operations parameters such as feed rate and cutting speed on machining-induced residual stress are examined [45]. The finite element approach is used to investigate the impact of machining parameters such as feed rate and cutting speed on surface roughness and residual stresses in milled components. [46].

3. Residual Stress in High-Speed Machining

In a high-speed machining process, heavy and slow cuts are replaced by fast, lighter cuts in order to increase the quality as well as efficiency during machining operations. But, the increasing machining process parameters of spindle speed, feed rate and material removal rate during machining operations can cause residual stress in the machined components. So, the influence of high-speed machining to the residual stress of machined parts are analyzed in different studies. To ensure the machined surface quality and residual stress during machining operations, a prototype of deformation caused by thermo-mechanical stresses considering tool flank wear in high-speed machining Ti-6Al-4V is proposed [47]. Distribution of Mechanical stresses created by cutting tool edge (a) and cutting tool flank wear (b) during machining operations are shown in the figure 5 [47]. Mechanical loads and rubbing heat sources caused by tool flank wear become major factors influencing the machined surface when tools are worn. Deeper plastic deformation is caused by the additional thermo-mechanical stresses caused by tool flank wear at the tool-workpiece interface [47].

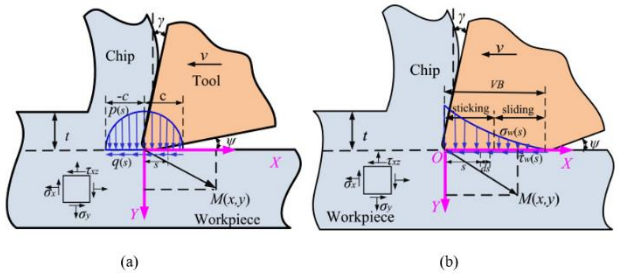


Figure 5. Distribution of mechanical stresses created by cutting tool edge (a) and cutting tool flank wear (b) during machining operations [47].

Finite element analysis and analysis of curved chip formation is proposed to model and minimize residual stress during high–speed machining operations of AA7075–T651 alloy [48]. In high-speed cutting of superalloy Inconel718 based alloys, a parametric method is developed to predict and minimize surface residual stress [49]. The impact of high speed machining operations on residual stress in magnesium alloys was examined in order to predict and reduce residual stress during machining operations. [50]. Analysis and X-ray measurements of machined parts are discussed to determine the effects of spindle rotational speed, feed speed, and tool condition on residual stress in high speed machining7075 aluminum alloy [51].

4. Effects of Cutting Forces and Cutting Temperatures to the Residual Stress

In the chip formation process, the cutting forces generate heat in the cutting zone which can leads to the residual stress in the machined components. The component's surface heats up and expands as a result of the machining process. Plastic flow, which is limited to the surface layer, then helps to relieve this expansion. When the heat is withdrawn from the surface layer, it expands, causing a tensile residual tension at the workpiece's surface. The impact of a combination of plastic deformations and thermal to the generated residual stresses of machined parts is shown in the figure 6 [52]. As a result, in order to analyze and decrease the residual stress in the machined parts, the cutting forces as well as cutting temperatures are analyzed in different studies.

To evaluate and reduce residual stress in machined ZE41 magnesium alloy components, the impact of temperature stresses and cutting forces on residual stress are studied [53]. The structure of generated residual stress in the cutting zone is presented in order to evaluate and reduce residual stress in milling operations due to cutting temperature and cutting forces [54].

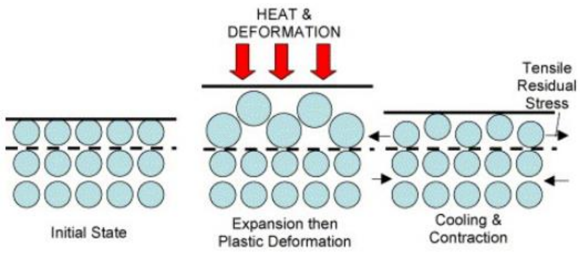


Figure 6. The impact of a combination of plastic deformations and thermal to the generated residual stresses of machined parts [52].

In order to investigate the effects of cutting forces and cutting tool wear on the residual stress of machined components, applications of modified machining parameters is investigated [55]. To enhance the performance of machined parts by reducing residual stress, the influence of rake angle-based Johnson-Cook material constants on the evaluation of temperatures generated and residual stresses in Al2024-T3 milling operation is discussed [56]. The influence of cutting tool materials, machining parameters such as depth of cut and cutting speeds on residual stress in machined parts are studied in order to minimize residual stress in machined parts [57]. Predictive model of surface stress distribution after end milling based on cutting force and induced heat in the cutting zone is analyzed to reduce residual stress in machined parts [58].

5. Effects of Coolant to Residual Stress of Machined Parts

To decrease the generated heat in the cutting zone and increase cutting tool life during machining operation, the coolant is used. So, the chip formation process can be implemented with low temperature which can decrease the generated residual stress in the machined parts [59]. A thorough analysis of the influence of flood and MQL coolants on the machinability and stress corrosion of super duplex stainless steel has been conducted in order to propose cooling and lubrication conditions in machining operations and extend the component's service life [60]. To control cutting temperature and force, as well as promote a longer tool life and better surface finish, the influence of cutting fluid on machining force, temperature, and residual stress are investigated [61]. Cryogenic coolant's influence on machinability and machining-induced residual stress in difficult-to-machine materials The Ni–Cr alloy studied in order to boost the efficiency of machined components [62]. The cooling techniques in milling operations of SA516 are proposed to minimize residual stress and deformation error in machined components [63]. The influence of cutting tool temperatures on the residual stress of machined components was examined using statistical models of residual stress in minimum quantity lubrication machining operations [64]. The influence of standard lubricating oil and carbon dioxide coolant on residua stress and surface quality of Inconel 718 are presented in order to enhance the service life of machined components [65]. The effects of low-temperature coolants on residual stress and surface finish when machining AISI 316L stainless steel are studied in order to increase the machined parts' reliability. [66].

6. Effects of Cutting Tool Wear, Edges and Radius to the Residual Stress

The cutting tool geometries and parameters can impact to the cutting forces as well as cutting temperatures during chip formation process. The influence of different parameters of cutting tool such as cutting tool wear, edges and radius to the generated residual stress during machining operations is studied in order to increase efficiency in the machining operations. The machining parameters of feed rate and feed normal forces are decreased by increasing the rake angle of cutting tool during machining operations. Thus, increasing rake angle can reduce residual stresses In the perpendicular direction [67]. More material was ironed on the workpiece subsurface as the ploughing depth increased, resulting in an increase in compressive residual stress [68]. As is shown in the figure 7, the trend of uncut chip thickness decreasing can reduce the ploughing effect to decrease the residual stress in the machined components [68].

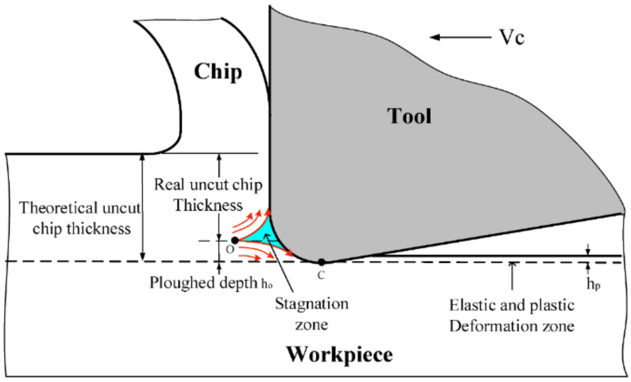


Figure 7. Uncut chip thickness effect to the residual stress of machined part [68].

By changing of tool wear, the surface residual stress is changed from compressive to tensile. Peak compressive stresses demonstrated a strengthening tendency when the reverse transition position was deeper. As tool wear is increased, the total depth of residual stress is also moved deeper into the workpiece [69]. The enhancement of cutting tool corner radius can decrease cutting force, but hardly influence cutting temperature which can decrease the residual stress in the machining operations [70]. The increase of the tool nose radius leads to an increase of the thrust force which can increase the residual stress in the machined parts. Moreover, the residual stress of machined parts are increased by increasing of the tool wear during machining operations [71]. The influence of cutting tool geometry on residual stresses in machining operations of IN-718 is shown in the figure 8 [72]. The wider contact area between the cutting edge and the accumulated material ahead of the cutting edge induces greater ploughing impact and therefore greater mechanical deformation of the material at that position when the chamfered and honed edge is used. The ploughing effect is minimized with the chamfered cutting edge. So, with the honed and chamfered cutting edge of the cutting tool, the state of residual stress is extremely compressive [72].

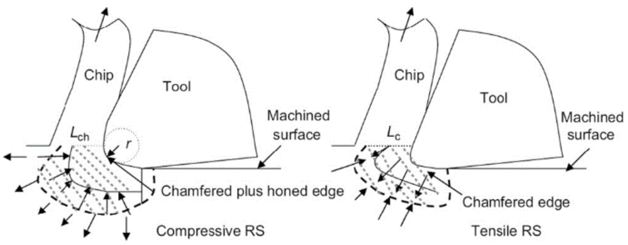
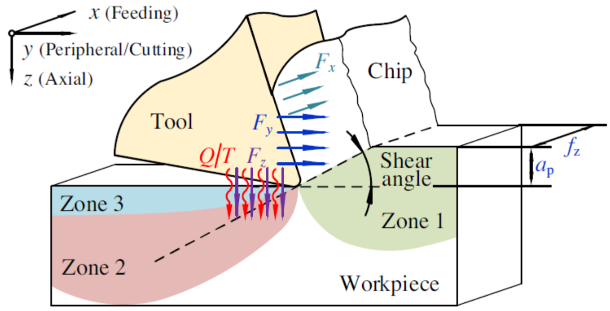


Figure 8. The influence of cutting tool geometry on residual stresses in machining operations of IN-718 [72].

The application of a multi-physics method to simulate residual stress for orthogonal cutting Ti-6Al-4V is explained in order to control residual stress distribution by evaluating tool wear morphology [73]. In order to enhance surface quality and reduce residual stress of machined components, the influence of cutting tool wear on residual stresses caused during turning operations of a 15-5 PH stainless steel is discussed [74]. In order to investigate the effects of tool wear on surface roughness, dimensional quality, and residual stress while turning the IN718 hard-to-machine alloy, the cutting tool parameters are analyzed and modified [75]. Optimized cutting parameters in inclined end milling operations for minimal surface residual stress is discussed to reduce residual stress in machined components [76]. The effect of tool wear and tool edge radius on distribution of residual stresses in situ TiB2/7050 Al matrix alloy composites during turning process is discussed in order to analyze and reduce residual stress by improving the cutting tool parameters [77]. To analyze the surface integrity as well as residual stress during turning operations of inconel 718, influence of tool wear conditions to cutting force is analyzed [78]. The effect of cutting tool parameters such as, cutting force, temperature and tool corner radius on residual stresses in machining operations is studied in order to minimize residual stress in machined parts [70]. In order to minimize residual stress in machined components, cutting tool parameters such as tool outer diameter are investigated and analyzed [79]. To reduce residual stress in machined parts, the impact of cutting tool parameters such as tool wear rate on surface quality and residual stresses is investigated [80].

7. FEM Simulation for Prediction and Analysis of the Residual Stress

Applications of the FEM analysis in the analysis and minimization of the residual stress in different research works are investigated in order to increase quality of machined parts. To calculate the thermal distribution, residual stress, and deflection of machined components, the finite element method can be used. To determine residual stress in machined products, a FEM analysis of residual stress distribution and cutting forces in orthogonal cutting with different initial stresses is proposed [54]. As shown in figure 9, the orthogonal structure is used to qualitatively explain the relationship between cutting loads



and the stress field.

Figure 9. The relationship between cutting loads and the stress field in the chip formation process [54].

To estimate residual stress in machined parts, a measurement of surface residual stress after end milling depending on cutting temperature and force is presented [58]. Figure 10 illustrates the growing theory of surface residual stress against thermal and mechanical pressures. As it is obtained, the surface residual stress increases rapidly with temperature and cutting forces when the depth of cut is fixed and the feed, but this growth is relatively mild when the depth of cut is fixed and the feed is changed [58].

To analyze and decrease the residual stress during machining operations of Ti-6Al-4V parts, applications of the finite element methods by considering microstructural analysis is presented [81]. So, the residual stress distribution model is proposed in the study in order to be minimized by using the optimized machining parameters.

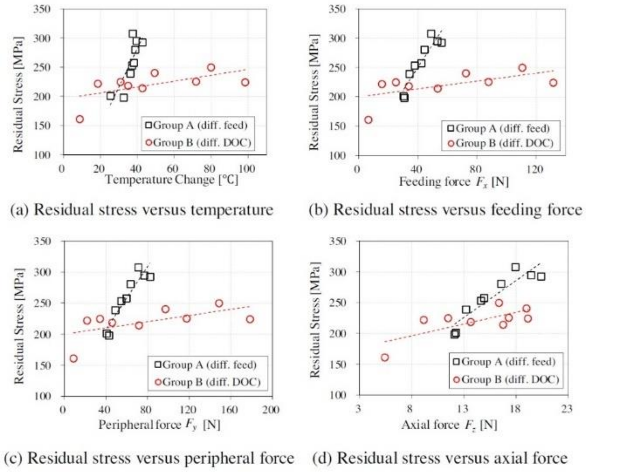


Figure 10. The growing theory of surface residual stress against thermal and mechanical pressures [58].

8. Analytical and Semi-Analytical Modelling of Residual Stress

To minimize deformation and tensile stress during machining operations, a mathematical method to predict machining distortion of produced parts caused by residual stress is presented [82]. To increase surface quality of machined parts, the final machining deformation error of thin-walled component is analyzed and minimized using original residual stress based on a semi-analytical method [83]. To evaluate and reduce residual stress during machining operations, a semi-analytical method for detecting machining deflections of thin-walled parts is presented by considering machining-induced and blank initial residual stress [84]. To analyze and reduce residual stress during machining operations, an experimental method to predict residual stress due to mechanical load during orthogonal milling is presented [85]. To predict and reduce residual stress in orthogonal cutting operations, an application of mathematics for residual stress calculation in complex orthogonal cutting operations is investigated [86]. To provide reliable predictions of the thermal and mechanical effects to the machined components, a mathematical modelling strategy to estimate residual stresses in single-track laser deposited IN718 is developed [87].

To improve the quality of machined parts by reducing residual stress, a multi-criterion collection of the optimized parameters for high-speed milling of aluminum alloy Al7075 thin-walled parts is described [88]. In order to accurately predict and minimize residual stress during milling operations, a theoretical model of machining-induced residual stresses in three-dimensional angular milling processes is discussed. Figure 11 shows 3D views of tool and chip formation processes during machining operations to model cutting operations as well as residual stress in machined parts [89].

Chip forming force and ploughing force are the two main sources of loads during the cutting process. Chip forming force is generated in the shear region, while ploughing force is generated by the tool edge's contact with the workpiece [90]. In order to evaluate residual stress in machined parts, a new mathematical modelling for residual stress created by thermal-mechanical load during orthogonal machining is created [91]. The stresses at point **M** are elastic if the cutting tool tip is far away from the object. The stress load in point **M** steadily increases as the tool approaches, and when the tool hits point **B**, the stress state of the object point satisfies the yield condition and plastic deformation begins.

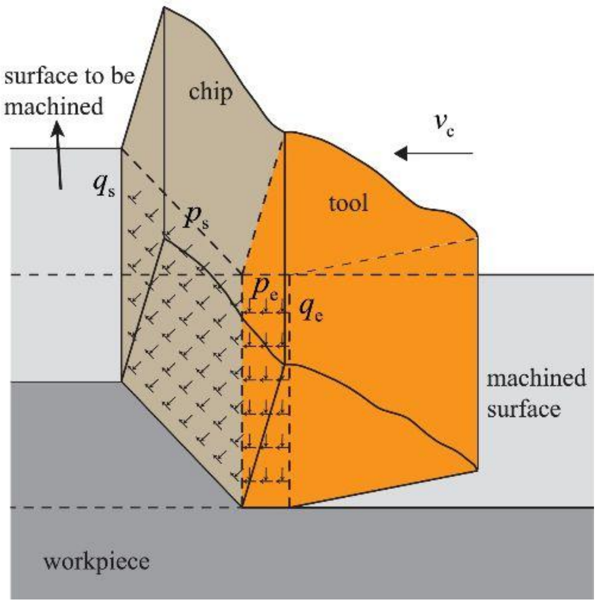


Figure 11. 3D views with tool and chip formation process during machining operations [89].

The plastic deformation becomes more noticeable as the cutting progresses on the workpiece. The cutting tool is steadily moving away from the object point after passing through directly above. Then, when stress reaches zero, the object point experiences the opposite elastic-plastic deformation. This is the entire mechanism that operates on point **M** of the object due to the combined effects of machining-induced thermal-mechanical forces. The process of residual stress creation in the orthogonal machining operations is shown in the figure 12 [91].

9. Numerical Simulation of Residual Stress

In order to study and reduce residual stress in machining operations, a simulation model of the effects of elastic anisotropy and grain size on the machining of AA2024 is described [92]. To analyze and reduce the machining induced residual stress, simulation and modeling of machining distortion of pre-bent aluminum alloy plate is investigated [93].

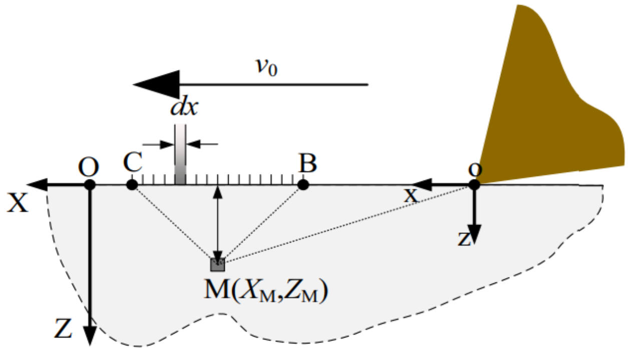


Figure 12. The process of residual stress creation in the orthogonal machining operations [91].

To evaluate and reduce near-surface residual stresses during machining, Statistical and Mathematical Simulations of Machining-induced Residual Stresses in Ball End Milling of Inconel 718 is presented [94]. In order to model and measure residual stress in machined parts, a statistical evaluation of residual stress created by the turning-burnishing method of AISI 4140 steel is presented [95]. To monitor part deflection and deformation during machining of low rigidity thin-wall panels, a three-dimensional finite element based numerical simulation of machining of thin-wall components with varying wall limitations is investigated [96]. To optimize the machining operations and obtain the displacements and stresses during the cutting operations, numerical simulation of the system "fixture–workpiece" is presented [97]. The effect of the machining process on residual stress accumulation and machining accuracy is investigated using mathematical models to optimize the machining process plan and ensure component compliance with tolerance specifications [98].

10. Residual Stress in the Aluminum Alloys

To evaluate and reduce residual stress in machined aluminum alloy parts, deformation error caused by residual stresses in milling aerospace aluminum alloy parts is investigated [99]. To improve the service life of AL alloys machined components, the impact of residual and stress micro-hardness in Turning process of Aluminum 7075 alloy is presented [100]. Analytical simulation of residual stress in nickel-aluminum bronze alloys during end milling operations is presented in order to reduce machining induced residual stress in the manufactured components [101]. Evaluation of surface residual stress distribution in deflection machining process for aluminum alloy is provided to analyze and reduce residual stress during machining operations [102]. To improve the surface finish and edge quality of machined components, a finite element and analytical method of microstructure during machining of high-volume fraction SiCp/Al composite alloys is presented [103]. To improve the quality of machined parts by reducing residual stress during machining operations, residual stress and displacement simulation on aviation aluminum alloy parts through milling process optimization is presented [104]. Machining of aluminum alloys and the generated residual stress during machining operations is reviewed in order to increase quality of al alloys machined parts [105].

11. Residual Stress in the Biomedical Implant Materials

Due to the importance of working life as well as safety of the machined parts from biomedical implant materials, the machining induced residual stress should be investigated in order to be decreased [106]. Residual stress during machining operations has been studied in order to enhance the functional efficiency, life, and sustainability of machined biomedical implant materials [107]. The machinability of medical metallic implants is discussed to decrease the residual stress and increase the life and sustainability of produced parts [108]. To reduce residual stress and distortion during machining operations, several residual stress evaluation methods are applied to coarse-grained biomedical implant castings [109]. To reduce residual stress in the generated biomedical implants, topology optimization to model support systems to prevent residual stress induced structure failure in laser powder particles metal during machining operations is presented [110]. To boost corrosion resistance in machined components, the surface quality and corrosion performance of biomedical magnesium-calcium alloy processed by hybrid milling-burnishing operations are investigated [111]. Residual stress calculation during machining operations of complex-shaped coarse-grained cobalt–chromium biomedical castings materials is presented to analyze and decrease the residual stress in the machined parts [112].

12. Residual Stress in the difficult-to-Cut Materials

To increase efficiency in machining operations of difficult to cut materials, surface integrity as well as residual stress are studied in different research works. To explore the impact of cutting parameters on the residual stress of machined components, a study of residual stress production in hard to cut materials is presented [113]. To analyze and decrease the residual stress during machining operations of hard to cut materials, a review of recent achievements is presented by Sutanto and Madl [2].

12. 1. Residual Stress in the Nickel Based Alloys

For hard-to-machine alloys with low thermal conductivity that encourage wide thermal gradients, such as nickel-based superalloys, tensile residual stresses may be as high as the yield strength. Tensile residual stresses are frequently produced on the surface of nickel alloys machined parts. [114]. So, residual stress stability should be considered when evaluating their effect on the component's final mechanical actions [115]. To analyze and decrease the residual stress of in dry machining of nickel-based alloy parts, 3D modeling of recrystallized layer depth and residual stress is presented by Jafarian [116]. Figure 13 illustrates the detection of residual stress during machining operations of nickel-based alloys. Both experimental and numerical findings of the analysis indicate the same general pattern and magnetite of residual stress.

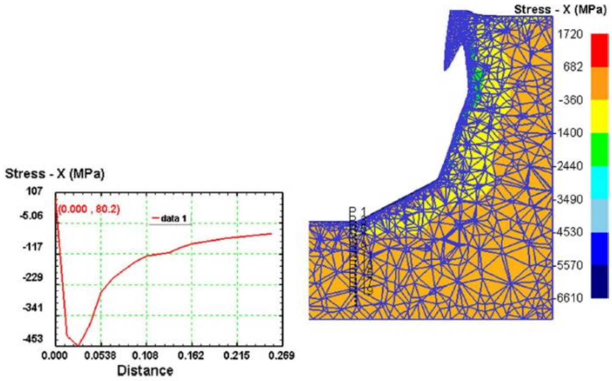


Figure 13. The detection of residual stress during machining operations of nickel-based alloys [116].

Experiments and calculations utilizing finite element simulation of machining induced residual stresses are provided to reduce residual stress in machined IN718 nickel-based alloy components [117]. To reduce residual stress distribution during machining operations, an experimental work of primary residual stress and fatigue quality during turning operations of nickel-based superalloy Inconel 718 is presented [118]. Surface integrity and residual stress caused by tool wear impact in the machined surface of titanium and nickel alloys are examined in order to improve the performance of machined components [119].

12. 2. Residual Stress in the Titanium Based Alloys

Titanium and its alloys have excellent mechanical properties at high temperatures, high corrosion and acid resistance and high strength-to-weight ratio which make it ideal for a wide variety of applications. As the alloys are hard to be machined, the generated residual stress in the machined titanium-based alloys parts are analyzed in the different studies. The residual stress in machined parts is analyzed and reduced by simulating machining strain of titanium alloys aero engine applications using energy principles methods [120]. Simulated and measured residual stress after outside diameter turning process are shown in the figure 14 [120].

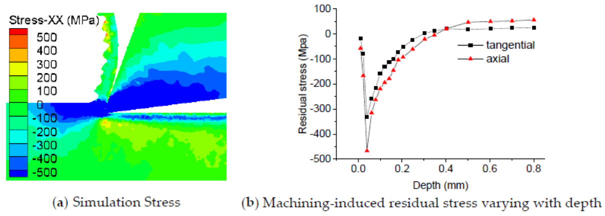


Figure 14. Simulated and measured residual stress after outside diameter turning process [120].

A finite element simulation of residual stress with microstructural consideration is proposed to determine the impacts machining conditions such as feed rate and surface cutting speed on residual stress during machining of Ti-6Al-4V [81]. As a result, the effects of machining process parameters to the residual stress of machined components are analyzed to increase quality of produced parts.

12. 3. Residual Stress in the Inconel Based Alloys

Due to outstanding properties of the inconel based alloys, the produced parts from the alloy are widely used in the aerospace, automotive, and biomedical industries. As a result, the generated residual stress in the machined Inconel Based Alloys parts should be studied to be minimized [121]. To improve component fatigue life, an analysis of residual stresses caused by dry turning of difficult-to-machine materials is presented [122]. In-depth residual stress distribution in machining Inconel 718 is shown in the figure 15 [122]. Residual stresses begin as tensile at the surface and progressively change to compressive values beneath the surface before stabilizing at the level found in the work material prior to machining (around zero MPa).

To study and reduce residual stress in machined components, the impact of tool chamfer edge geometry on residual stress in the turning operation of Inconel 718 are investigated [123]. The tensile residual stress in the turning process of Inconel718 superalloy is measured experimentally and designed to reduce residual stress using optimized machining operations [124]. To generate the residual stress distribution model in the machined components, a numerical approach to the segmented chip effect on residual stress distribution in orthogonal cutting of Inconel718 is investigated [125]. To improve the service life of machined components, surface quality and residual stress in laser-assisted machining of nickel-based superalloys are studied [126].

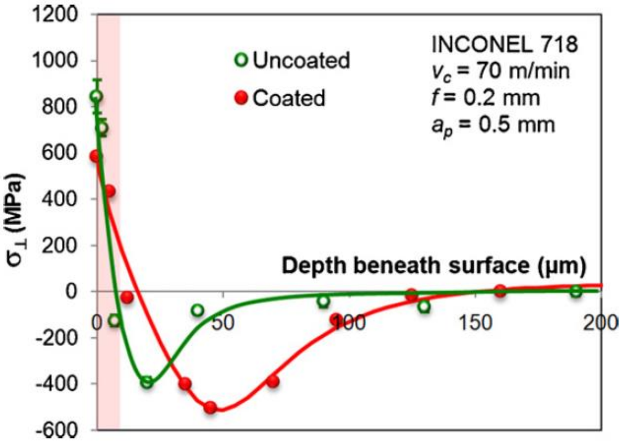


Figure 15. In-depth residual stress distribution in machining Inconel 718 [122].

12 .4. Residual Stress in the Stainless-Steel Alloys

Because of their high corrosion and oxidation resistance, stainless steels have a wide range of applications. However, due to specific properties such as high mechanical and microstructural sensitivity to strain and stress rates, these materials are considered difficult to machine which can generate residual stress in the produced parts [127].

To evaluate the residual stress caused in the machining operations of stainless steel components, predictive modeling of microstructure shifts, micro-hardness, and residual stress in machining of 304 austenitic stainless steel is discussed [128]. An experimental investigation and microstructural evaluation of residual stresses in hard machining of AISI 52100 steel is proposed in order to assess and reduce residual stress during machining operations [129].

Residual stress during machining operations is investigated to determine the effect of machining-induced surface residual stress on the initiation of stress corrosion cracking in 316 austenitic stainless steel [130]. The evaluation of the machined surface of hardened AISI 4340 steel in turning operations using roughness and residual stress parameters is presented in order to improve the quality of machined parts by reducing residual stress [131]. To improve the quality of machined parts by reducing stress corrosion cracks, the effect of milling operations on the production of stress corrosion cracks in austenitic stainless steel is presented [132]. The surface integrity and residual stress of AISI 4340 Hardened Alloy Steel during machining operations are examined in order to improve the quality and performance of the machined components [133]. Application of response surface methodology in obtaining optimized machining parameters such as spindle speed and depth of cut is investigated in order to reduce residual tension, cutting force, and surface roughness in end milling of S50C medium carbon steel [134].

Recent development of the machining induced residual stress is shown in the Table 1.

Table 1: Recent development of the machining induced residual stress

Topic of research work	Papers	Finding/ Discoveries
Effects of Machining Process Parameters	[40]	The influence of process parameters on residual tress of machined parts in turning operations is examined and optimized machining parameters is introduced.
	[43]	Numerical analysis into the influence of machining parameters such as feed rate and cutting speed on residual stresses in orthogonal cutting operations is applied.
	[45]	The influence of cutting operations parameters such as feed rate and cutting speed on machining-induced residual stress are examined and new process parameters are

		presented.
Residual Stress in High-Speed Machining	[47]	a prototype of deformation caused by thermo-mechanical stresses considering tool flank wear in high-speed machining Ti-6Al-4V is presented in terms of residual stress minimization process.
	[48]	Developed models of finite element analysis is proposed minimize residual stress during high–speed machining operations of AA7075–T651 alloy.
	[51]	To determine the effects of spindle rotational speed, feed speed, and tool condition on residual stress, analysis and X-ray measurements of machined parts are discussed.
Effects of cutting forces and cutting temperatures to the Residual stress	[53]	To evaluate and reduce residual stress in machined ZE41 magnesium alloy components, the influence of temperature stresses and cutting forces on residual stress are studied.
	[56]	The influence of rake angle-based Johnson-Cook material constants on the evaluation of temperatures generated and residual stresses in Al2024-T3 milling operation is discussed.
	[58]	Predictive model of surface stress distribution after end milling based on cutting force and induced heat in the cutting zone is analyzed to reduce residual stress in machined parts.
Effects of Coolant to Residual Stress of Machined Parts	[60]	To propose cooling and lubrication conditions in machining operations, an advanced analysis of the influence of flood and MQL coolants on the machinability and stress corrosion of super duplex stainless steel has been conducted.
	[63]	to minimize residual stress and deformation error in machined components, advanced techniques of cooling in milling operations of SA516 are proposed.
	[65]	The influence of standard lubricating oil and carbon dioxide coolant on residua stress and surface quality of Inconel 718 are presented in order to enhance the service life of machined components.
Effects of Cutting Tool Wear, Edges and Radius to the Residual Stress	[73]	The application of a multi-physics method to simulate residual stress for orthogonal cutting Ti-6Al-4V is explained in order to control residual stress distribution by evaluating tool wear morphology.
	[76]	Optimized cutting parameters in inclined end milling operations for minimal surface residual stress is discussed to reduce residual stress in machined components.
	[79]	In order to minimize residual stress in machined components, cutting tool parameters such as tool outer diameter are investigated and analyzed.
FEM Simulation to Predict and Analyze the Residual Stress	[54]	FEM analysis of residual stress distribution and cutting forces in orthogonal cutting with different initial stresses is proposed to determine residual stress in machined products.
	[58]	To estimate residual stress in machined parts, a measurement of surface residual stress after end milling depending on cutting temperature and force is presented.
	[81]	To analyze and decrease the residual stress during machining operations of Ti-6Al-4V parts, applications of the finite element methods by considering microstructural analysis is presented.

Analytical and Semi-Analytical Modelling of Residual Stress	[84]	To evaluate and reduce residual stress during machining operations, a semi-analytical method for detecting machining deflections of thin-walled parts is presented by considering machining-induced and blank initial residual stress.
	[86]	To predict and reduce residual stress in orthogonal cutting operations, an application of mathematics for residual stress calculation in complex orthogonal cutting operations is investigated.
	[87]	A mathematical modelling strategy is developed to provide reliable predictions of the thermal and mechanical effects to the machined components.
Numerical simulation of Residual Stress	[93]	To analyze and reduce the machining induced residual stress, simulation and modeling of machining distortion of pre-bent aluminum alloy plate is investigated.
	[94]	To evaluate and reduce near-surface residual stresses during machining, Statistical and Mathematical Simulations of Machining-induced Residual Stresses in Ball End Milling of Inconel 718 is presented.
	[96]	To monitor part deflection and deformation during machining of low rigidity thin-wall panels, a three-dimensional finite element based numerical simulation of machining of thin-wall components with varying wall limitations is investigated.
Residual Stress in the Aluminum Alloys	[100]	The impact of residual and stress micro-hardness in Turning process of Aluminum 7075 alloy is presented to increase the service life of AL alloys machined components.
	[102]	Evaluation of surface residual stress distribution in deflection machining process for aluminum alloy is provided to analyze and reduce residual stress during machining operations.
	[104]	Residual stress and displacement simulation on aviation aluminum alloy parts through milling process optimization is presented.
Residual Stress in the Biomedical Implant Materials	[107]	Residual stress during machining operations has been studied in order to enhance the functional efficiency, life, and sustainability of machined biomedical implant materials.
	[109]	Several residual stress evaluation methods are applied to coarse-grained biomedical implant castings in terms of residual stress minimization methods.
	[112]	Residual stress calculation during machining operations of complex-shaped coarse-grained cobalt–chromium biomedical castings materials is presented to analyze and decrease the residual stress in the machined parts.
Residual Stress in the Nickel Based Alloys	[123]	The impact of tool chamfer edge geometry on residual stress in the turning operation of Inconel 718 are investigated.
	[124]	The tensile residual stress in the turning process of Inconel718 superalloy is measured experimentally and designed.
	[126]	To improve the service life of machined components, surface quality and residual stress in laser-assisted machining of nickel-based superalloys are studied.

Residual Stress in the Titanium Based Alloys	[120]	The residual stress in machined parts is analyzed and reduced by simulating machining strain of titanium alloys aero engine applications using energy principles methods.
	[81]	A finite element simulation of residual stress with microstructural consideration is proposed to determine the impacts machining conditions such as feed rate and surface cutting speed on residual stress during machining of Ti-6Al-4V.
Residual Stress in the Inconel Based Alloys	[122]	To improve component fatigue life, an analysis of residual stresses caused by dry turning of difficult-to-machine materials is presented.
	[124]	The tensile residual stress in the turning process of Inconel718 superalloy is measured experimentally and designed to reduce residual stress using optimized machining operations.
	[126]	To improve the service life of machined components, surface quality and residual stress in laser-assisted machining of nickel-based superalloys are studied.
Residual Stress in the Stainless Steel	[128]	To evaluate the residual stress caused in the machining operations of stainless-steel components, predictive modeling of microstructure shifts, micro-hardness, and residual stress in machining of 304 austenitic stainless steel is discussed.
	[130]	Residual stress during machining operations is investigated to determine the effect of machining-induced surface residual stress on the initiation of stress corrosion cracking in 316 austenitic stainless steel.
	[134]	The response surface methodology in obtaining optimized machining parameters such as spindle speed and depth of cut is applied in order to reduce residual tension.

13. Conclusion

Residual stresses from machining operations have a significant impact on distortion and fatigue life of machined components, reducing the quality and service life of the parts produced. As a result, the residual stress during machining operations is analyzed in different studies in order to be minimized. Thus, in terms of improving the performance of machined components in actual working conditions, predicting and minimizing residual stresses induced by machining operations is crucial. This paper evaluates recent advances in the analysis and reduction of machining induced residual stress. Different methods of the residual stress measurement Destructive Methods, Semi Destructive Methods and Non-Destructive Test (NDT) Methods are reviewed and compared in order to be

developed. In order to reduce residual stress in machined parts, the study examines parameters of machining process such as coolant, cutting tool wear, edges, and radius to residual stress. Analytical and semi-analytical modeling, numerical and FEM Simulation techniques are discussed in order to predict and minimize residual stress in machined components.

While there has been considerable improvement in the areas of residual stresses and distortion in machining operations, there are still many problems and difficulties to be solved. The most serious flaw in finite element analysis is its inadequate computational efficiency, which seriously restricts model complexity and reliability. It's difficult to consider the time-consuming nature of a three-dimensional cutting model. The disadvantages of analytical models for predicting residual stress in machining operations are specific to each machining problem. As a result, in order to provide practical solution for the residual stress modelling, the models should be developed for each case study. Artificial neural network as well as fuzzy logic algorithms applications may assist in the solution of this problem. Furthermore, recent advances in some areas, such as friction and thermal simulation, were not taken into account when designing the finite element models.

Optimized coolant systems regarding the residual stress as well as machining cost minimization can be studied in order to increase added value in process of part manufacturing. In order to reduce residual stress in machined components, the effects of cutting tool materials and new alloys of cutting tool inserts on machining-induced residual stress can be investigated.

Residual stress during machining operations of new materials in the aerospace applications such as alumina matrix composite and titanium matrix composites which are modified by microstructures with added reinforcement phases should be considered in order to be analyzed and decrease. Also, the effects of surface integrity to the residual stress as well as fatigue life of the new super alloys can be investigated in order to increase quality of machined parts.

To decrease the distortion error in the machining operations, magnitude and distribution of the residual stresses should be studied. As a result, the accuracy of machined parts can be improved. To improve the performance of component machining operations, relaxation techniques can be applied to machined parts. So, the fatigue life as well as working life of the machined components can be increased to provide more added values in the machining operations. Moreover, the distortion of parts due to the relaxation methods can be analyzed in order to be minimized. The impact of clamping methods of the workpiece during machining operations to the residual stress can be investigated in order to present the optimized clamping techniques in terms of residual stress minimization.

To decrease the generated residual stress in the machined components, topology optimization methods can be applied in the designing phase of parts in order to decrease the stress concentration points during machining operations. As a result, the machined parts can be produced with less amount of generated residual stress to increase efficiency in machining operations.

Machining induced residual stress by considering the environmental concern and green manufacturing can be studied in order to leads to cleaner machining operations. Residual stress as well as distortion of thin-walled parts during machining operations can be studied to be decrease. As a result, accuracy in the machining operations of then-walled parts such as impeller blades as well as turbine blades can be increased. The influence of vibration as well as chatter phenomena during machining operations to the residual stress of machined parts can be investigated in order to increase quality of machined parts.

The fields of distortion engineering and understanding the causes of distortion are still developing. To produce distortion-free pieces, further research and collaboration between industry and academia is needed. The effects of Compressive residual stresses in fatigue life enhancement can be studied in order to increase working life of the machined components. In high-sensitivity components that have closed geometric and dimensional tolerances, the amount of hyper-residual stress and how they are distributed are of particular importance. It is important to build a more precise and general analytical model. The Waldorf method, which is a basic slip line method that only considers geometry during the cutting process and ignores material properties, is used in the majority of current models. In order to improve the quality of machined parts, advanced and reliable models of part distortion prediction and control due to residual stress should be investigated in research studies. This study, as well as its implementation by industry, would result in major manufacturing cost savings, including lower operating costs. As a result, the warranty will be reduced and component life will be extended.

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