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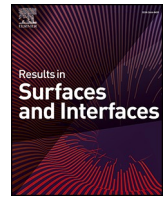
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Surface quality enhancement by constant scallop-height in three-axis milling operations

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ABSTRACT

The quality of machined part surfaces are under the impact of scallop height which should be analyzed and minimized. Achieving a uniform scallop-height is important for ensuring a smooth surface finish and maintaining consistent material removal across the machined surfaces during CNC machining operations. This approach helps to reduce material waste, tool wear and part production errors while ensuring consistent and high-quality of machined parts. Maintaining a constant scallop height can also help to reduce chatter and vibration during milling operations. The research work develops a virtual machining methodology to produce constant scallops through three-axis milling operations. The proposed approach examines free-form surfaces of workpiece in order to obtain free form surfaces curvatures. Then, free-form surfaces are separated into flat, convex and concave surfaces to provide optimized cutting tool variables in order to provide constant scallop height during CNC cutting tool paths. Achieving a constant scallop height involves optimizing cutting parameters such as feed rate, spindle speed, and step over. To calculate the optimized machining parameters of feed rate, speed of spindle and step over, the Taguchi optimization methodology is utilized in the study. Then, the machining variables of feed rate, speed of spindle and step over are optimized to achieve the uniform scallop height during milling operations of free-form surfaces. As a result, using optimized machining parameters during machining operations, the surface roughness of machined components are reduced by 23.8%. So, the proposed virtual machining method can enhance surface quality of machined parts during CNC milling operations of free-form-surfaces.

1. Introduction

Scallop height, also known as stepover or axial depth of cut, refers to the distance between consecutive passes of the cutting tool along the machined surface. It is referred to as the highest regional thickness of chip volume that remains uncut from the surface of part during the chip generation. In the milling of free-form surfaces, the scallop-height should be carefully monitored and managed in terms of improving machined surfaces integrity. Therefore, the parameters of cutting operation can be adjusted to create the consistent height of scallop through milling to improve accuracy and precision of component production using CNC machining operations. By keeping the scallop height constant, several benefits can be achieved, leading to enhanced surface quality in milling operations. Also, maintaining a constant scallop height

helps in minimizing the spacing between tool paths, reducing the occurrence of visible tool marks on the machined surface. Constant scallop height aids in achieving more predictable and consistent machining results in order to improve accuracy and dimensional control of machined parts (Feng and Li, 2002). Moreover, the cutting tool experiences more uniform wear during machining operations by optimizing the cutting conditions with a constant scallop height. This can lead to extended tool life, reducing the need for frequent tool changes and improving overall machining efficiency (Kasim et al., 2019). Maintaining a constant scallop height helps in reducing machining vibrations, resulting in a more stable machining process and improved surface finish during metal cutting operations. As a result, surface quality of machined parts and efficiency of part production can be enhanced by maintaining a constant scallop height during machining

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operations.

The concept of constant scallop height in milling operations is a strategy to enhance surface quality by promoting a uniform and smooth finish on machined parts which studied in different research works. Jia et al. (2019) produced redesigned cutting tool paths to provide continuous scallop height throughout milling of complicated curved surface components. Segonds et al. (2019) established a theoretical analysis by taking the impacts of feed rate into account to simulate and minimize the scallop height in milling operations using torus-end cutters. Kukreja and Pande (2019a) developed a cutting-edge software system by employing numerical parameter estimation techniques to obtain the scallop height in free form surfaces cutting operations. Calculating height of scallop during CNC machining of a free-form area is implemented by Kukreja and Pande (2019b) to determine the heights of scallops at different locations on the surface using numerical curve fitting approaches. Steady scallop-height tool pathway development during three-axis sculpted surface cutting is presented by Feng and Li (2002) to generate paths for cutting tools by employing fewer and quicker steps than the current methods while maintaining the required machining precision. Three-axis separate data point milling utilizing continuous scallop-height tool pathway is presented by Liu et al. (Liu et al., 2012) to analyze and modify machining paths during CNC machining operations.

Huang et al. (2019) examined a methodology for modifying tool trajectories which uses adaptive intervals to maintain consistent scallop height while milling pocket surfaces with plungers. To provide a uniform scallop-height while free form surfaces have been milled, Shchurov and Al-Taie (2017) provided an inventive method of trajectory adjustment for cutter. Lin et al. (2014) provided updated cutting tool pathways optimization addressing the consistent scallop height of machined surfaces to enhance quality of surface throughout free form surfaces milling using 5-axis milling machines. Senatore et al. (2013) provided redesigned cutting tool trajectories for free form surface milling operations to achieve equal scallop height. Liang et al. (2021) created an innovative cutting tool route optimization system to supply the universal iso-scallop during machining processes of free form surfaces. Balabokhin and Tarbuton (2017) created a technique for adjusting tool paths according to the cutting tool performance measure to give iso-scallop during 3-axis CNC machining of free-form rectangle meshed patterns. Liu et al. (2020) described an advanced technique for an effective iso-scallop cutting tool path to improve the manufactured items surface condition using three-axis dispersed cloud machining operations. Fountas et al. (2019) offered optimized cutting tool paths to improve surface properties by producing regular scallop throughout milling of sculptured surfaces. To improve surface quality of machined parts during five-axis free-form surfaces cutting operations, the machining strip thickness is optimized by Liang et al. (Wu et al., 2018). Assessment of surface quality during milling utilizing a ball nose end mill is presented by Varga et al. (2023) to enhance the surface quality of produced parts in the machining of molds. To accurately estimate the topography of the surface during ball-end CNC machining operations, the topography of the machined surfaces are simulated by Xu et al. (Xu et al., 2018).

Improved barrel cutter construction and cutter route optimization system are examined by Luo et al. (2016) to accomplish the consistent scallop height and improve quality of machined free form surface. The machined component's scallop height is examined by Duvedi et al. (2015) to enhance surface attributes in terms of cutting large polygonal using a 5-axis mill and a flat milling blade. Wang et al. (2015). Presented an enhanced tool path generating technique to satisfy a consistent height of scallop in polishing operations on convex surfaces. Cao et al. (2015) proposed optimal cutting tool routes to calculate the iso-scallop height through machining processes of free form surfaces. Li et al. (2019) utilized physical shell modeling and reverse-compensation modification to improve spiral surface quality of milled surfaces. Xu and Li (2019) described the optimization of the cutting tool utilizing digital pictures in order to mill free form materials with consistent scallop depth. Su et al.

(2020) described a sophisticated cutting tool pathways improvement to provide a constant scallop level in terms of free form edges cutting procedures. Meta-heuristic algorithms for assessing the collapse risk of steel moment frame mid-rise buildings is presented by Karimi Ghaleh Jough and Şensoy (2016) in order to provide a better risk management strategy in steel moment frames. Steel Moment-Resisting Frame Dependability via Interval Analysis using the FCM-PSO Method is studied by Karimi Ghaleh Jough and Şensoy (Karimi Ghaleh Jough and Şensoy, 2020) to enhance accuracy and decrease execution time in calculation of seismic fragility curves. In order to incorporate epistemic uncertainty and increase calculation accuracy, Karimi Ghaleh Jough and Beheshti Aval (Karimi Ghaleh Jough and Beheshti Aval, 2018) implemented uncertainty analysis through development of seismic fragility curve for an SMRF structure using an adaptive neuro-fuzzy inference system based on fuzzy C-means algorithm. Ghasemzadeh et al. (2022) discuss identifying and contextualizing factors of infrastructure projects in order to identify and demonstrate the current deficiency of using BIM for infrastructure projects.

Virtual machining methodologies are proposed by Soori et al., 2013, 2014, 2016, 2017; Soori and Asmael, 2021a, 2021b) to examine and develop CNC machining procedures in digital environments. Soori and Arezoo (2022c) discussed an analysis of residual stress induced by machining to evaluate and reduce residual stress during metal-cutting processes. Soori and Arezoo (2022a) studied several tool wear prediction techniques to extend the life of cutter through machining processes. To decrease residual stress and integrity of surface in grinding operations, Soori and Arezoo (2022b) proposed the Taguchi optimization approach and enhanced machining constants. In order to enhance energy usage effectiveness, data quality and accessibility using the supply chain, Dastres et al. (Dastres et al., 2022) proposed a survey of RFID-based wireless manufacturing techniques. To acquire the best milling configurations, Altintas and Merdol (2007) also proposed methods and applications of virtual machining system. To analyze the impacts of coolants to tool wear, temperature of cutting and surface quality of machined parts, Soori and Arezoo (2023) implemented a research work. To enhance accuracy in 5-Axis CNC milling operations of turbine blades, deformation errors is compensated by Soori (2023). To enhance accuracy and productivity in industry 4.0, applications of intelligent robotic systems are reviewed by Soori et al., 2024.

According to a review of previously published papers, the virtual machining methods are not implemented to the optimized machining parameters in terms of scallop-Height minimization of milling operations. As a result, the study is novel study in order to improve production precision and performance during component manufacture using CNC machine tools.

The virtual machining methodology in milling of free from surfaces is proposed in the research work to provide constant scallop height through three-axis CNC milling operations. The proposed approach looks at the workpiece's free-form surfaces to determine their curvature. In order to provide optimum cutting tool variables with regard to the minimization of scallop height during CNC cutting tool pathways, free-form surfaces are then divided into flat, convex, and concave surfaces. Optimizing cutting parameters such as feed rate, speed of spindle and step over is essential process to achieve a consistent scallop height during machining operations. The Taguchi optimization process is utilized to achieve the optimal feed rate, spindle speed, and step over machining parameters. During free-form surface milling processes, the machining parameters such as feed rate, spindle speed, and step over are adjusted to achieve the lowest possible scallop height. A sample workpiece with free form surfaces is milled using three-axis CNC machine tools to confirm the research's findings. The scallop height of the cutting tool pathways during the end milling operations is then calculated from the machined surfaces using the ZeGage Optical surface profiler. So, the measured height of scallop for the milled part are obtained and presented by using the diagrams in terms of presenting the performance of the developed approach in the study. As a result, the suggested virtual

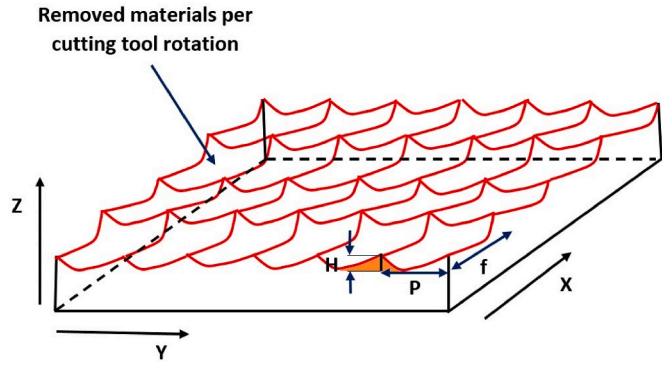


Fig. 1. The height of scallop for milled surfaces along the X and Y axes.

machining approach in the research has the potential to enhance the accuracy and surface finish of free-form surfaces when utilizing CNC milling machines.

Section 2 outlines the mathematical algorithms governing scallop heights during milling on flat, convex, and concave surfaces. In Section 3, the procedure for partitioning a surface into flat, convex, and concave regions is presented. The application of the Taguchi optimization methodology to achieve consistent scallop heights is discussed in Section 4. The proposed virtual machining methodology is illustrated in Section 5. section 6 is provided to support the research. section 7 describes the research outcomes.

2. Scallop-height in the machined surfaces

Two different types of scallop heights are used in milling operations to produce the pattern on machined surfaces. As a consequence of the feed rate cutter along the path of machining, the tool-nose cut the part in height of scallop which is seen in the X-axis direction (f). Also, the step over (p) and cutting tool nose radius during the milling operation cause the height of scallop in the Y-axis direction to be higher than the tool's edge (Wang et al., 2013). Fig. 1 depicts the machined component's scallop height in the X and Y axes.

The feed rate for each rotational period of cutter can be presented as,

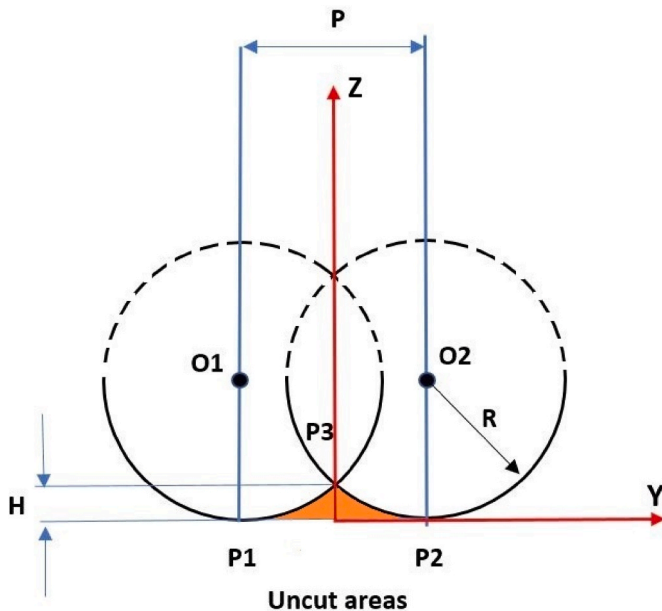


Fig. 2. Scallop-height in flat surface.

$$f = \frac{F_c}{S} \quad (1)$$

where, f is feed rate for each rotational period of cutter (mm/rev), F_c and S are rate of feed during milling (mm/min) and spindle speed (rev/min) respectively.

3. Workpiece surface division into flat, concave and convex surfaces

The free-form surfaces of workpiece can be separated into flat, concave, and convex surfaces to calculate the height of scallop along the Y-axis during milling operations. To divide the surfaces of workpiece into flat, concave and convex surfaces, the proposed method by Li et al. (2014) in multi-axis CNC machining based on surface subdivision is considered. The mean curvature H is during machining paths can be presented as (Li et al., 2014),

$$H = \frac{1}{2} \left(\frac{EN - 2FM + GL}{EG - F^2} \right) \quad (2)$$

where E , F , and G are the elements of the initial matrix of a surface A form the surface $S(u, v)$ at a point (x, y, z) (Li et al., 2014),

$$A = \begin{bmatrix} S_u \cdot S_u & S_u \cdot S_v \\ S_v \cdot S_u & S_v \cdot S_v \end{bmatrix} = \begin{bmatrix} E & F \\ F & G \end{bmatrix} \quad (3)$$

and L , M , and N are the elements of the initial matrix of a surface B (Li et al., 2014),

$$B = \begin{bmatrix} S_{uu} \cdot n & S_{uv} \cdot n \\ S_{vu} \cdot n & S_{vv} \cdot n \end{bmatrix} = \begin{bmatrix} L & M \\ M & N \end{bmatrix} \quad (4)$$

Then, the local surface machining complexity can be obtained as (Li

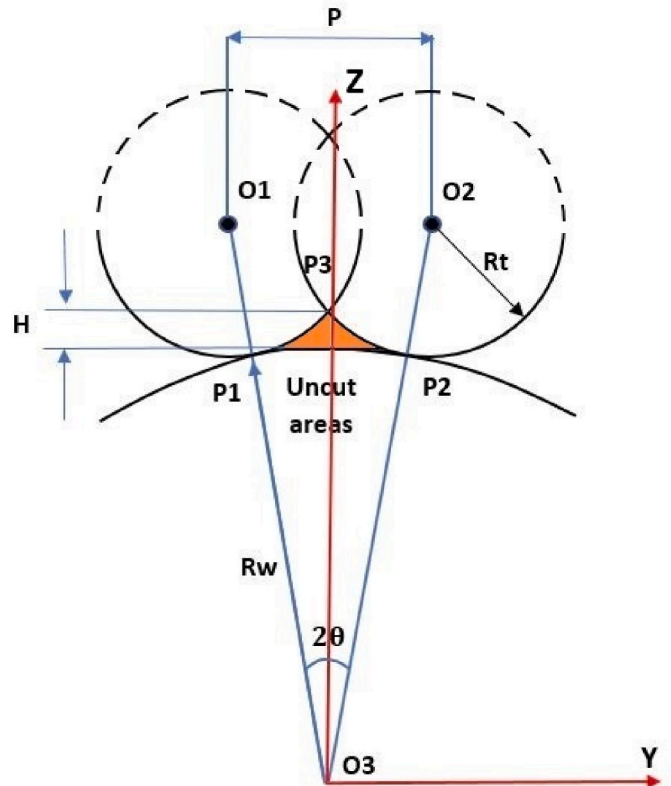


Fig. 3. Scallop-height in convex surface.

et al., 2014),

$$C_r^i = K_{max}^i - k_{min}^i = \frac{1}{r_p^i} - \frac{1}{r_v^i} \tag{5}$$

$$p = \frac{Rw}{(Rw + H)(Rw + Rt)} \sqrt{2[(Rw + Rt)^2 + Rt^2](Rw + H)^2 - [(Rw + Rt)^2 - Rt^2]^2 - (Rw + H)^4} \tag{8}$$

where K_{max}^i , k_{min}^i , r_p^i and r_v^i indicate the greatest mean curvature, lowest mean curvature, maximum radius of mean curvature, and lowest mean curvature radius of a grouping zone, respectively. The mathematical formulae can be applied to the surfaces to model the height of scallop

$$p = \frac{Rw}{(Rw - H)(Rw + Rt)} \sqrt{2[(Rw + Rt)^2 + Rt^2](Rw - H)^2 - [(Rw + Rt)^2 - Rt^2]^2 - (Rw - H)^4} \tag{9}$$

through milling. Fig. 2 depicts the height of scallop in milling of flat surfaces.

To compute the scallop height throughout flat surfaces using the geometric relationships in Fig. 2, the nose radius of cutter can be presented as,

$$R^2 = \left(\frac{p}{2}\right)^2 + (R - H)^2 \tag{6}$$

Thus

$$p = 4\sqrt{R^2 - (R - H)^2} \tag{7}$$

where R is radius of cutter nose, H is the height of scallop and p is the space between cutting tool paths.

Fig. 3 depicts the height of scallop while convex surface milling process.

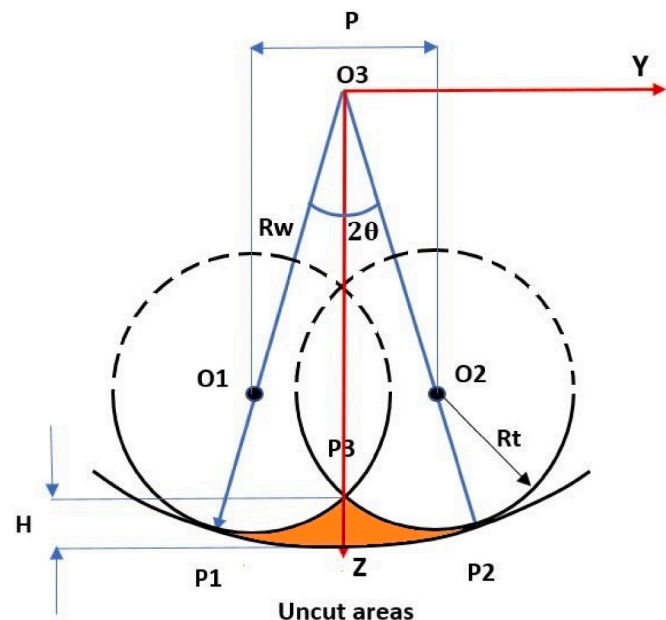


Fig. 4. Scallop-height in concave surface.

In order to get the path interval throughout machining processes on convex surfaces,

where Rw is radius of sample part curvature, Rt is the cutting tool radius, P is the cutter route spacing, and H is height of scallop. Fig. 4 shows the height of scallop throughout concave surface end milling.

Therefore, it is possible to determine the path interval of the milling cutter throughout milling process as,

4. The Taguchi optimization methodology to uniform scallop-heights

The Taguchi methodology is a powerful and reliable optimization strategy that can considerably improve performance of processes using a minimal number of experiments. Taguchi optimization is a robust design methodology that is widely used in various industries, including CNC

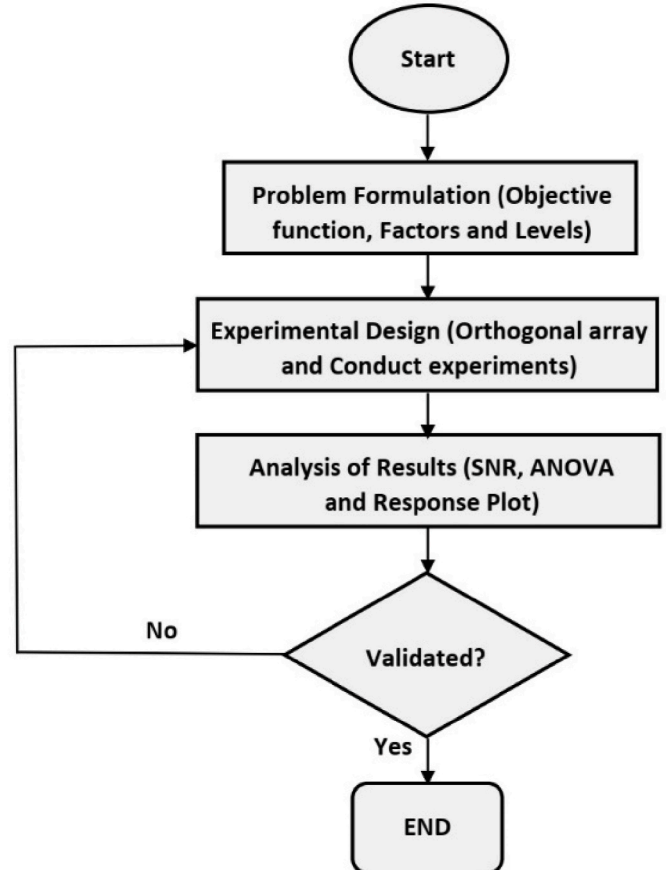


Fig. 5. The technique of Taguchi optimization.

machining operations. By following the Taguchi optimization approach, manufacturers can improve the CNC milling operations by finding the optimal combination of parameter settings, leading to increased efficiency, higher quality, and reduced costs. Fig. 5 depicts the workflow for the Taguchi optimization methodology.

To evaluate the influence of machining operations on response qualities, the signal-to-noise ratio (S/N) for each control variable is calculated. The signals show how the influence on average answers has changed over time. The noises estimate the effect of noise components on deviations from average responses while taking into account how sensitive the experiment's outcome is to noise. Various quality standards, such as the nominal-the-better, the lower-the-better, and the higher-the-better, are used by the response analysis approach. To reduce the response during the process of EDM parameter optimization, the S/N ratio is chosen using the lower-the-better criteria. The following is a representation of the smaller-is-better S/N ratio (Bement, 1989).

$$S/N = -10 \log \frac{1}{n} \left(\sum_{i=1}^n y_i^2 \right) \quad (10)$$

where, n is the number of occasions the experimental works were carried out and y_i is the median measurement value of experimental result i .

The "lower-is-better" category was applied to calculate the signal-to-noise ratios to provide constant scallop-Height during milling processes. So, the optimal machining variables of spindle speed, feed rate and step over are obtained to improve machined items' surface quality using uniform scallop-Height during milling.

5. Scallop-height minimization by using virtual machining methodology

Utilizing the Matlab programming language, the study constructs a

virtual machining methodology to minimize the height of scallop through free form surface milling. The system receives as inputs the height of scallop restriction, machining codes, conditions of cutting, cutter shape, and a CAD image of the workpiece. The proposed virtual machining methodology looks at the workpiece's free-form surfaces to determine their curvature. In order to offer optimum cutting tool variables with regard to the minimization of scallop height during CNC cutting tool pathways, workpiece surfaces are then divided into flat, convex, and concave surfaces. The Taguchi optimization process is utilized to achieve the optimal feed rate, spindle speed, and step over machining parameters. Then, as free-form surfaces are being milled, the machining variables of feed rate, spindle speed, and step over are tuned to obtain minimum scallop height. Thus, utilizing the virtual machining methodology, the optimized machining parameters of rate of feed, step over and spindle speed are calculated to improve machined items' surface quality during CNC machining procedures. The process diagram for virtual machining, which creates constant scallop height through milling operations to improve the machined parts surface quality, is depicted in Fig. 6.

6. Validation

To verify the presented procedure in the study, sample workpiece is machined using the 3 The 5-axis Kondia HM 1060 CNC machine tool. The dimensions of sample part during experimental work is shown in Fig. 7.

Fig. 8 shows the cutting tool paths to produce the sample workpiece.

The cutting tool in the in the experimental works is four fluted ball nose end mills made of Tungsten carbide with 15 mm in diameter, 70 mm overall, and 35 mm in flute length. The recommended cutting conditions in the experimental works are based on previous published research works (Escamilla-Salazar et al., 2017; Singh et al., 2020). Thus,

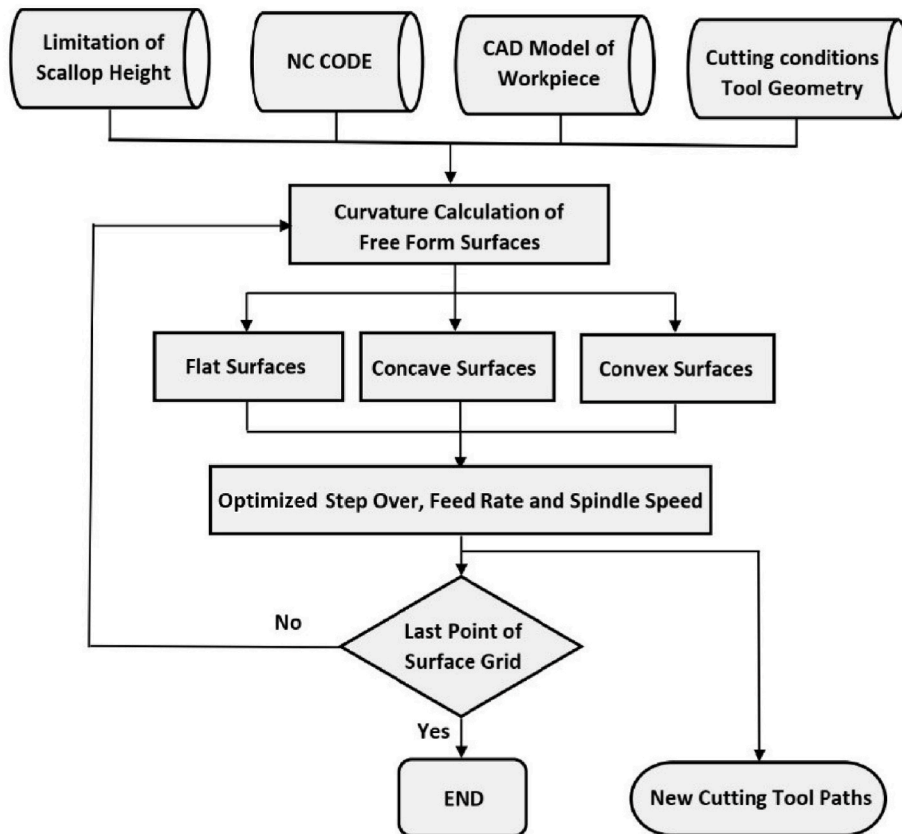


Fig. 6. The flowchart for producing uniform scallop height using virtual machining method.

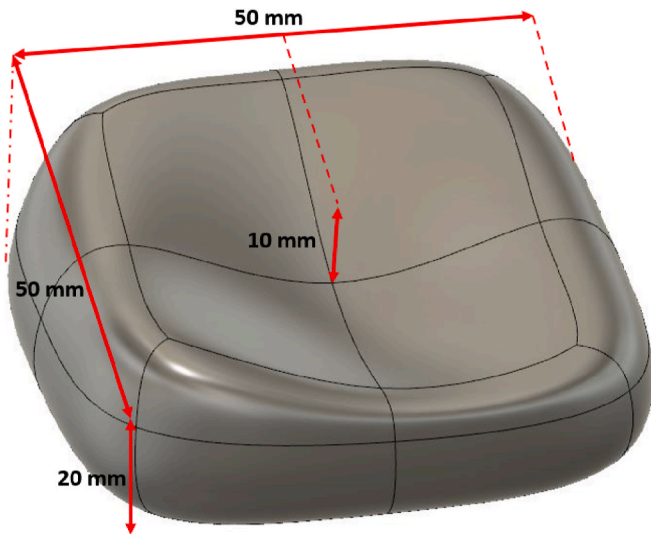


Fig. 7. The experiment's sample workpiece.

spindle rotational speed is 10,000 rpm, with a step over of 5 mm, and rate of feed of is also selected as 400 mm/min in roughing operations. Then, spindle rotational speed is 10,000 rpm, with a step over of 4 mm, and rate of feed of is also selected as 280 mm/min during finishing operations of machined part. The material of workpiece is Al7075-T6. The experiments are repeated for 10 times in order to reduce the effect of errors in the obtained results. As a consequence, Fig. 9 depicts the machined sample workpiece.

To achieve constant scallop-height during milling, the Taguchi method-based response surface analysis approach is used to identify the optimum machining settings for feed rate, spindle speed, and step over. The signal-to-noise ratios for amounts of scallop height during milling process have been determined through using "lower-is-better" category. Therefore, using the developed virtual machining procedure in the study, the optimized machining parameters of spindle speed, step over and rate of feed are obtained as 12000 rpm, 0.5 mm and 210 mm/min respectively. ZeGage Optical surface profiler measures the machined surfaces to determine the scallop-height of milled surfaces through milling operations. To quantify the surface quality of the sample component, the examination of optical surface integrity approach splits the light into two paths, while one of which moves to an exact reference

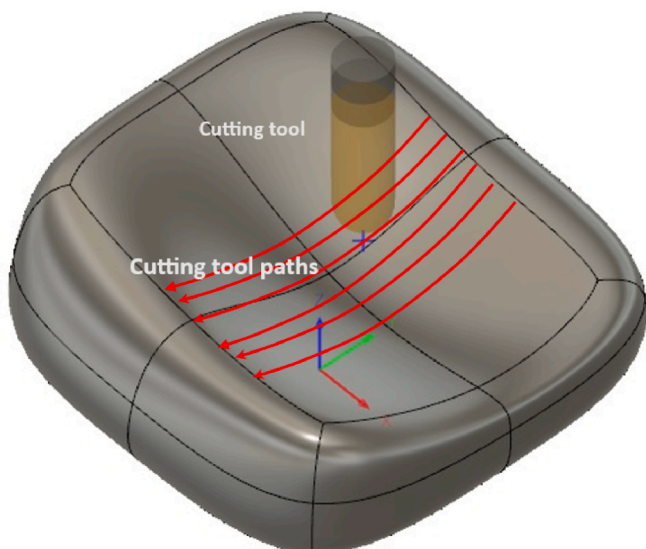


Fig. 8. The cutting tool paths.

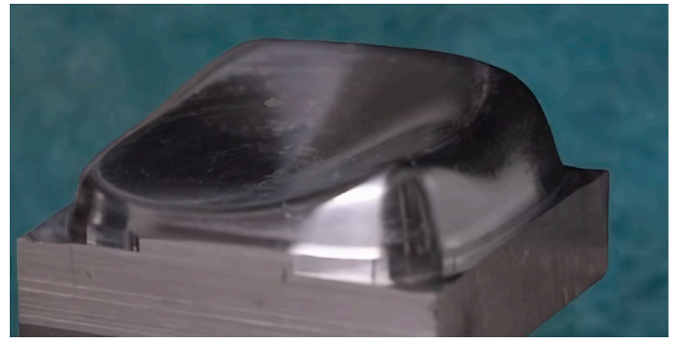


Fig. 9. Machined sample workpiece with free form surfaces.

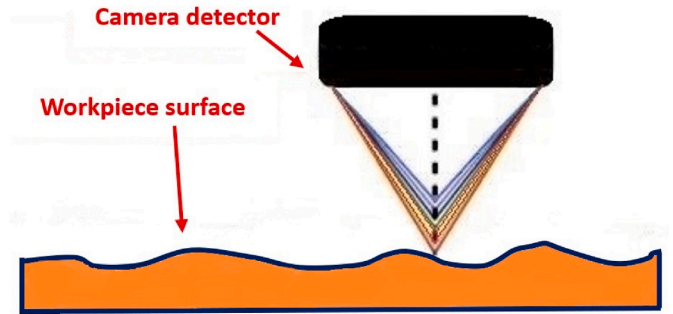


Fig. 10. Obtaining surface quality of sample part using a 3D optical surface measuring device.

surface, while the other moves to the sample surface. At a camera detector, the reflections from these two surfaces smash, producing a intensity of dark and light pattern. As a result, the sample workpiece's surface properties are revealed by the constructive interference. Fig. 10 illustrates the operation of a 3D optical surface measurement technique to determine the characteristics of a sample part's surface.

Fig. 11 illustrates the procedure for measuring the height of scallop for milled surfaces.

Thus, the measured surface roughness for the selected line in horizontal direction of machined sample part without and with optimized machining parameters are shown in Fig. 12.

Furthermore, the measured surface roughness for the selected line in vertical direction of machined sample part without and with optimized machining parameters are shown in Fig. 13.

As a consequence, applying the optimized machining variables, the maximum height of scallop for the milled and measured part is achieved as 5 μm . Thus, the suggested virtual machining technique can improve the surface quality of free from surfaces milling operations utilizing 3-axis CNC milling machine tools.

7. Conclusion

The scallop height of the surfaces throughout chip formation process is determined by the uncut volumes boundaries between two adjacent machined surfaces. It is the maximum of the volume height which remains uncut from the material surfaces of workpiece through the chip production process. To enhance the surface's machining quality, the height of scallop should be evaluated and adjusted. The research work presents a virtual machining technique for end milling free form areas with uniform scallop height while using a 3-axis CNC cutting machine. The suggested method determines the free-form surfaces curvature by looking at the workpiece's free-form surfaces. The next step is to divide free-form surfaces into flat, convex, and concave surfaces in order to give optimum cutting tool variables with relation to the restriction of

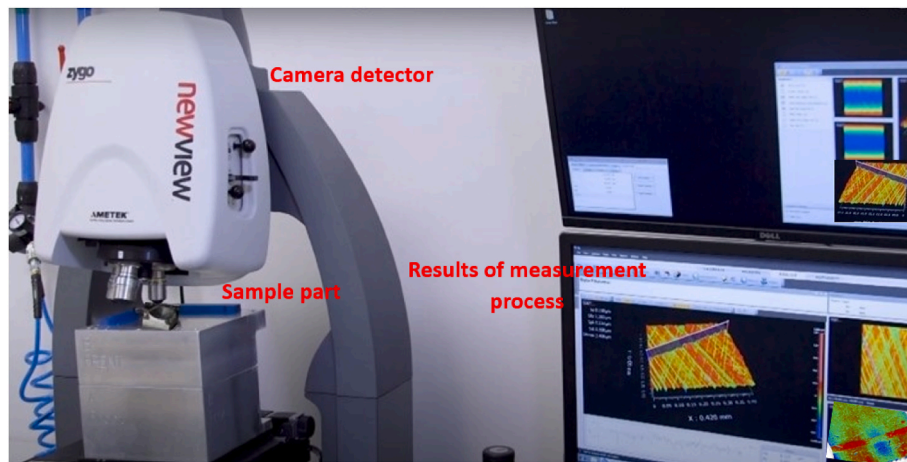


Fig. 11. The scallop's height measurement process using the ZeGage optical surface profiler.

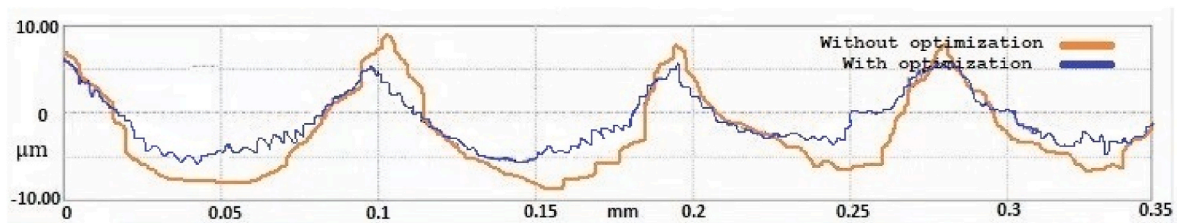


Fig. 12. The measured surface roughness for the selected line in horizontal direction of machined sample part without and with optimized machining parameters.

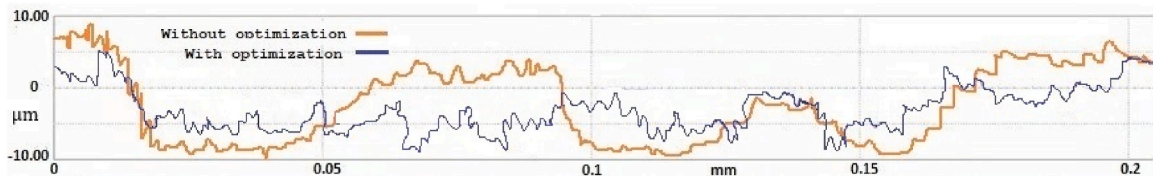


Fig. 13. The measured surface roughness for the selected line in vertical direction of machined sample part without and with optimized machining parameters.

scallop height during CNC cutting tool pathways. The Taguchi optimization process is applied to acquire the optimal feed rate, spindle speed, and step over parameters for machining. Therefore, using the proposed methodology, optimized machining variables for step over, speed of spindle and rate of feed are produced to achieve the constant height of scallop for the milled surfaces. A workpiece containing within free form surfaces is then milled, and the surfaces of the milled part are optically evaluated, to create optical 3D surface texture of milled surfaces. Thus, utilizing the optimum machining setting, the maximum height of scallop for the milled and measured part is achieved as $5 \mu\text{m}$. Moreover, using the optimized machining parameters, surface roughness of machined part is decreased by 23.8%. As a result, the height of the scallop is reduced and the surface quality of the machined items is improved utilizing the created virtual machining technique utilized in the investigation. The virtual machining approach can be employed to enhance the surface characteristics of produced items when 5-axis CNC milling operations are performed on free form surfaces. The concepts represent prospective areas of research for the authors.

While the constant scallop height strategy can be beneficial in certain scenarios, it is essential to consider its limitations and evaluate whether it is the most suitable approach based on the specific machining requirements and the properties of the workpiece material. Tool Wear and breakage, adaptability to geometry, programming complexity and increased machining time are some limitations associated with scallop height strategy in enhancing the surface quality of milled parts.

Future research works in cutting tool materials can lead to tools with

improved wear resistance and cutting edge retention. Further advancements in toolpath optimization algorithms can provide more efficient and precise cutting tool movements, reducing vibrations and improving surface finish of machined parts. Integration of advanced sensing technologies for in-process monitoring can also enable real-time feedback on tool wear, cutting forces, and other relevant parameters. Moreover, active vibration control systems may be implemented to counteract vibrations in real-time. The capabilities of study can be expanded in multi-axis in order to provide more complex toolpaths and improve access to difficult-to-reach areas. This can result in better surface quality by reducing the need for multiple setups.

CRediT authorship contribution statement

Mohsen Soori: Writing – original draft, Validation, Software, Methodology, Conceptualization. **Foad Karimi Ghaleh Jough:** Writing – review & editing, Visualization, Validation. **Behrooz Arezoo:** Supervision, Resources, Project administration.

Declaration of competing interest

We are interested to submit our manuscript to Results in Surfaces and Interfaces as outstanding journal in order to be considered for publication.

Data availability

No data was used for the research described in the article.

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