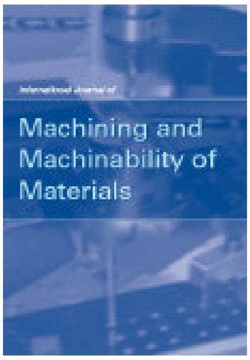

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Evaluation of different milling strategies on the performance of aluminium thin-walled parts

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Abstract: Achieving a good quality and performance accuracy during milling thin-walled parts is a challenging task associated with several industries. Therefore, the careful selection of the milling strategy is of utmost importance to obtain the best process performance. Accordingly, this paper studies various milling strategies' influence on the production effectiveness of thin-walled elements made of aluminium 5083 alloy. Machining time, surface roughness, and thin-wall deformation are the output measured responses to evaluate the process's effectiveness. Four milling strategies: parallel spiral, zigzag, parallel spiral with clean corner, and overlap spiral, selected using MasterCAM software, are implemented at fixed cutting conditions. The results showed that the parallel spiral is the best milling strategy for minimum surface roughness, wall deflection error, and thickness error with values of 0.1982 mm, 0.186°, and 0.23 mm, respectively, compared to other milling strategies. However, the overlap spiral strategy produces the worst thin-wall surface and higher wall deformation.

Keywords: thin-wall; milling strategy; aluminium alloy; effectiveness; machining time; surface roughness; wall deformation.

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1 Introduction

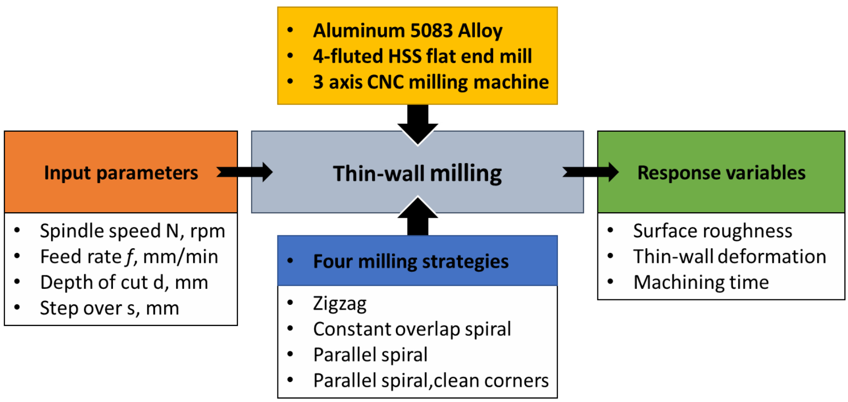
In the recent manufacturing era, there has been an increasing demand to decrease the final product's total weight while maintaining sufficient strength, surface quality, and dimensional accuracy. Therefore, thin-walled elements made of lightweight materials; such as titanium and aluminium; have a wide range of industrial applications such as in the aerospace and automotive industries (Kurpiel et al., 2023). Aluminium and its alloys are lightweight materials that are characterised by low density, high strength-to-weight ratio, corrosion and fatigue resistance over other metals properties (Pinar et al., 2016). Therefore, they are utilised in a wide range of industrial applications such as airframe structures, automobile and shipbuilding bodies, dies/moulds, turbine blades, housings, and enclosures (Leite et al., 2015; Zariatin et al., 2017). Typically, a thin-wall refers to a wall having a thickness between 1 and 2.5 mm with an aspect ratio of more than 5 (Bolar et al., 2018b). Thin-walled components usually have poor stiffness because of their large area-to-thickness ratio. For that reason, the common problem that the thin sections elastically deform during machining of thin-walled parts. Thus, the computer numerical control (CNC) end milling process is preferred in the case of thin-walled elements manufacturing due to low cutting forces, low cutting temperature, short machining time, and better surface finish (Leite et al., 2015; Kuczmaszewski et al., 2017). During end milling, the thin-wall's thickness is gradually reduced in machined layers to remove material as much as possible in the shortest time. As a result, the thin-wall may deflect under the cutting force, which negatively affects the geometry dimensions and the machined surface quality (Mejbel et al., 2022). Owing to the previous reasons, improving the dimensional accuracy and surface finish of machined thin-walled elements is challenging to achieve better process performance. CAD/CAM software are recently becoming important for producing the correct milling strategy and selecting the optimum one (Seguy et al., 2008; Ma et al., 2018).

Several research studies have been reported to investigate the different aspects of machining thin-walled aluminium parts. According to the investigation conducted by Kuczmaszewski et al. (2016), it was found that the milling strategy in relation to machining direction significantly affect the surface roughness parameters of the tested aluminium alloy EN AW-2024 thin-walled components. Different milling strategies; high performance cutting (HPC), HPC combined with conventional finishing operation, and high speed cutting (HSC); and machining directions (longitudinal and transversal) were applied. In another research work, Kuczmaszewski et al., (2017 and Zawada-Michałowska et al. (2021) stated that the milling strategies had a direct influence on the efficiency of the machined thin-wall elements made of different aluminium alloys in terms of geometrical accuracy, deformation, and machining time. Annoni et al. (2015) investigated the effect of two tool path strategies (waterline Z-level and overlapping step support) on the cutting forces, wall thickness, and flatness deviation when thin-wall micro-milling of carbon steel (C40). Das et al. (2016) implemented five different milling approaches to machine aluminium 2024 alloy thin-wall components and compared their influence on the wall thickness and surface roughness. The results showed that milling with gradual increase in depth of cut with a constant feed rate approach efficiently reduced the dimensional errors and surface roughness. The same group studied the effect of varying input parameters, i.e., feed per tooth, tool diameter, axial and radial depth of cut on the cutting force and surface roughness in Bolar et al. (2018b) and part deformation (Bolar et al., 2018a) of thin-wall aluminium 2024 alloy with thickness of 1.25 mm. It was observed that increasing feed rate and cutting depth resulted in higher surface roughness and wall deflection. In further work; for the same material and process; the cutting forces, temperature generated at workpiece surface, and residual stresses were experimentally investigated and simulated during roughing and finishing of aluminium alloy thin-wall parts (Li et al., 2015; Bolar and Joshi, 2017). Xiang and Yi (2021) studied the control of milling strategies during micro milling of different titanium alloy thin-wall structures through milling forces control, deformation mechanism, and tool path optimisation, which can assist in improving the mill in quality as well as dimensional accuracy.

Another drawback occurs during machining of thin-walled products is the deformation of the machined thin-wall since the high material removal rate conditions cause the lack of the thin-wall's stiffness (Ma et al., 2018). Additionally, the cutting forces produce wall bending that affect the final quality in terms of thin-wall's thickness, deflection, flatness, and straightness (Kurpiel et al., 2023). In this context, Zariatin et al. (2017) examined the thickness of thin-wall when micro-milling of aluminium alloy 1100 blade micro-impeller, and 11.71 μm was the minimal thickness obtained despite the wall was designed to be 3 μm thick. Ramanaiah et al. (2018) analysed the impact of process parameters on the wall deflection and surface finish of aluminium alloy machined thin-wall. High cutting speed, low feed rate, and low depth of cut were recommended to minimise the wall deflection and high depth of cuts for better machined surface. Izamshah et al. (2013) tested the effect of changing the used end mill's helix angle on the wall deflection of aluminium 7076 alloy thin-wall with a 2 mm thickness. The wall deflection was found to be inversely proportional to the value of the helix angle. Mejbel et al. (2022) developed a new milling technique using simultaneous identical double-sided end cutter milling cutters to ensure stable and accurate thin-wall machining since the same cutting forces occurred on both wall sides; so each force cancelled out the other. The final results showed that the machined thin-walled structure had low errors in deflection, flatness, chattering, surface roughness, and 50% reduction in machining time. The surface roughness in the feed direction, surface roughness in the transverse direction, and thin-walled parts deformation were investigated during milling of Al alloy 5083 at various level of spindle speed, depth of cut, transverse size, and feed rate (Cheng et al., 2020).

Summing up, in the light of the previous literature survey, it is noted that very limited studies focus on studying the effect of different milling strategies on the process performance during machining of thin-walled parts. In addition, machining of thin-walled components essentially requires precise setting of machining parameters as well as the correct choice of milling strategy in order to obtain the desired process performance such as dimensional accuracy and surface quality. Moreover, other parameters such as the used workpiece material and milling tool influence the whole process's efficiency in relation to the selected milling strategy. In this perspective, this research paper mainly aims to experimentally investigate the effect of different milling strategies of CNC end milling process on surface roughness, dimensional accuracy, and machining time of thin-walled aluminium alloys. Four milling strategies using MasterCAM program software have been applied during milling thin-walled aluminium alloy elements for the sake of selecting the optimum performance of output responses at constant cutting speed, feed rate, and depth of cut. Based on the problem statement and the objective of this project, the experimental details of this work are illustrated in Figure 1.

Figure 1 Schematic of the experimental procedure (see online version for colours)



2 Experimental work

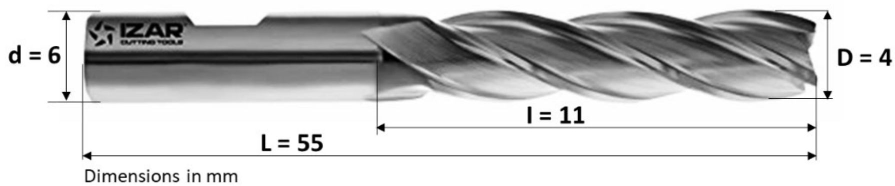
Aluminium 5083 alloy was used as workpiece blocks with dimensions of 80 × 70 × 30 mm^3. This alloy is distinguished by its low density, excellent thermal and electrical conductivity, and high resistance to be attacked by seawater and industrial chemicals, so it is widely used in many industrial applications such as shipbuilding, rail cars, vehicle bodies, and pressure vessels (Leite et al., 2015). The chemical composition and mechanical properties of Al 5083 alloy are given in Table 1, respectively. Milling experiments were carried out on a 3-axis CNC vertical milling machine. Four fluted high-speed steel end-flat mill (IZAR HSSE DIN 844N) of 4 mm diameter and 30° helix angle was used for milling of the thin-wall parts (see Figure 2). Other design factors were held constant at values of spindle speed 1,500 rpm and feed rate 200 mm/min. A schematic geometrical view of the sample is shown in Figure 3. The selected thin wall sample geometry is a simplification of the genuine industrial structures. The ‘unrestrained’ walls are common structures used in pocket elements. In addition, the current trend related to reducing the bulk of manufactured parts raise the value of wall thickness to be reduced. The machined thin walls have a thickness of 1 mm and a depth of cut of 20 and were machined in ten layers as the step-over depth was 2 mm. MasterCAM; a commercial CAM software program; was used to select the different milling strategies and generate the required G-codes for the CNC milling machine. Four milling strategies were employed, which were zigzag, constant overlap spiral, parallel spiral, and parallel spiral with clean corners, as shown in Figure 4.

Table 1 Chemical composition and mechanical properties of Al 5083 alloy

Chemical composition										
Element	*Al*	*Mg*	*Mn*	*Cr*	*Fe*	*Si*	*Zn*	*Ti*	*Cu*	*Others*
Weight %	93.99	4.18	0.873	0.0805	0.188	0.946	0.239	0.0199	0.003	Remainder

Mechanical properties			
Yield stress (Mpa)	*Tensile strength (Mpa)*	*Elongation (%)*	*Hardness (HRC)*
160	278	22	26.5

Figure 2 End mill used



Note: D – working part diameter, d – clamping part diameter, l – maximum depth of cut, L – overall length.

Figure 3 Schematic of thin-wall sample (see online version for colours)

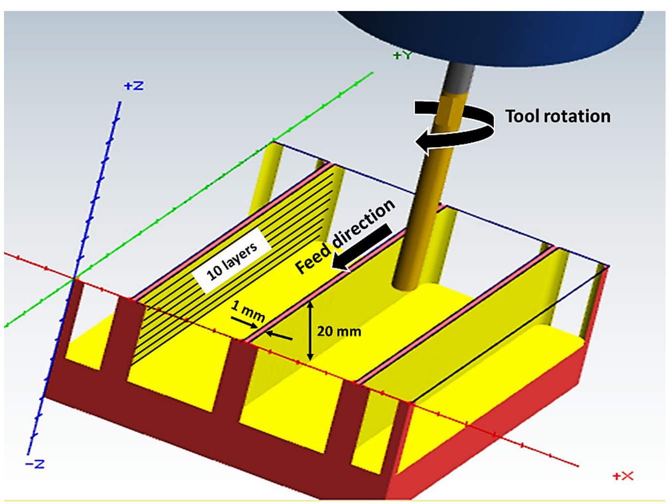
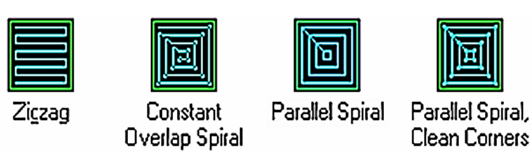


Figure 4 Milling strategies used in thin-wall milling (see online version for colours)



The effectiveness of the four used milling strategies was evaluated and compared in terms of machining time, surface roughness, and wall deformation. Surface roughness (Ra) of the floor surface was measured by using surface roughness tester PCE-RT 1200 device. Arithmetic mean roughness (Ra); the arithmetic average of the absolute values of the roughness profile ordinates; is one of the most effective surface roughness measures used in common engineering practice. Five measurements in the longitudinal direction were obtained to get the average value Ra with 2.5 mm cut-off and 12.5 mm sampling length. The wall deformation was evaluated in terms of the thin-wall thickness and deflection which were carried out using ImageJ-1.47 software. The wall thickness measurements were conducted at 20 positions along the depth of the thin wall then the average thickness was considered for this study.

3 Results and discussion

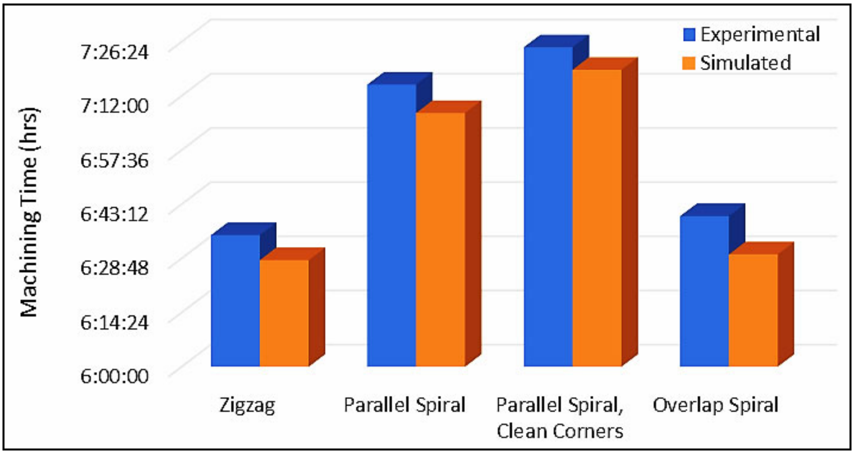
3.1 Machining time

Table 2 illustrates the results of the experimental machining time, MasterCAM software simulated time, and the difference between them for each milling strategy. To clarify the results and for more understanding point of view, A comparison between the actual CNC machining time and the simulated machining time by MasterCAM software program is presented graphically in Figure 5 in order to compare the performances of different milling strategies. Results on machining time show that zigzag strategy recorded the shortest machining time compared to the others machining strategies for both actual and simulated machining time with values of 6:35 hrs and 6:28 hrs, respectively. Overlap spiral strategy also shows less machining time of 6:40 hrs and 6:29 hrs for actual and simulated machining time, respectively. While parallel spiral and parallel spiral with clean corners take longer actual and simulated machining time, that can be related to the more additional movements of the cutting tool during these two types of tool paths. Although parallel spiral with clean corners recorded the longest machining time of 7:24 hrs and 7:18 hrs for experimental and simulated machining time, respectively, it shows the lowest variation in machining time of about $\Delta T \approx 5$ mins.

Table 2 Results of experimental and simulated machining time for different milling strategies.

Machining time / Milling strategy	Experimental machining time (hrs)	MasterCAM® simulated time (hrs)	Time difference (ΔT)
Zigzag	6:35:00	6:28:21	0:06:39
Parallel spiral	7:15:02	7:07:29	0:07:33
Parallel spiral, clean corners	7:24:56	7:18:58	0:05:58
Overlap spiral	6:40:03	6:29:53	0:10:10

Figure 5 Experimental versus simulated machining time for each milling strategy (see online version for colours)



3.2 Surface roughness

Surface roughness is the second measure of process effectiveness as it is considered a crucial tool to evaluate the process performance and product quality as well. Figure 6 shows the results of surface roughness (Ra) using the four different milling strategies. From the graph, it can be observed that parallel spiral strategy produced the least surface roughness, followed by zigzag strategy with Ra values of 0.1982 mm and 0.2455 mm, respectively. However, rougher surfaces with Ra ≈ 0.3176 and 0.3058 mm are generated when milling using overlap spiral and parallel spiral with clean corners strategies, respectively. Since the smaller diameter tool has poor rigidity, so chatters at tool-workpiece contact may occur and consequently worsens the machined surface quality. In addition, dry milling processes performed during this study may cause higher friction at the tool-workpiece interface due to the accumulation of the produced chips between the tool and workpiece surface, resulting in rough surface finish.

Figure 7 depicts the surface topography images of the machined surfaces of thin-walled elements obtained at each milling strategy used to clarify showing waviness, roughness, and milling marks appeared in different areas depending on the milling strategy used. These photographs show that the machined surface is relatively smooth when using parallel spiral, parallel spiral with clean corners, and overlap spiral strategy. However, clear salient marks are visibly observed on the machined surface during milling with zigzag strategy. This is because of the nature of the tool movement in the case of zigzag strategy that applies interrupted engagement pattern between the cutting tool's flutes and the workpiece surface in addition to fluctuating variation in immersion boundaries that creates deep valleys on the workpiece surface. So, it can be concluded that the milling strategy has an influence on the selected parameters of surface topography.

Figure 6 Surface roughness results with respective milling strategy (see online version for colours)

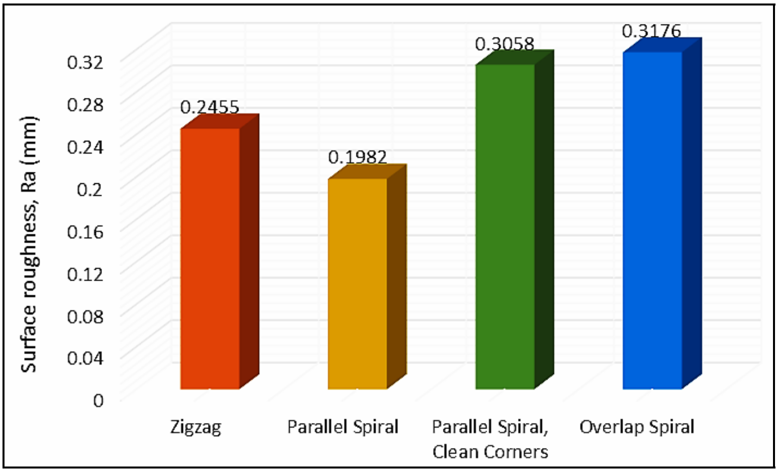
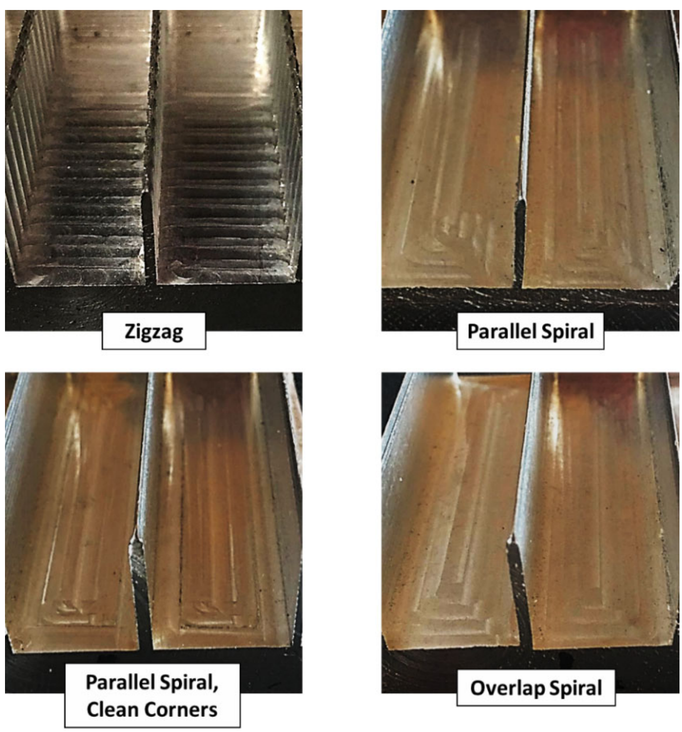


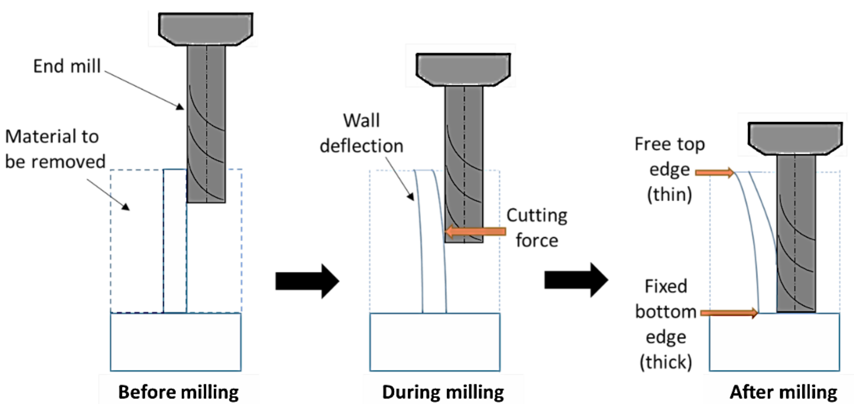
Figure 7 Images of the machined surfaces at different milling strategy (see online version for colours)



3.3 Wall deformation

Wall deformation is another essential evaluation feature to consider when selecting the appropriate milling strategy for machining thin-wall components. The primary common problem that arises during the machining of thin-walled elements is their elastic and plastic deformations, resulting in dimensional and geometrical errors. Figure 8 presents a schematic diagram of the wall deflection mechanism during thin-wall milling. As shown in Figure 8, when milling a thin-wall, elastic deformation occurs due to the effect of the cutting force applied by the cutting tool on the thin-wall, causing higher wall deflection at the free top edge. It is attributed to the fact that the free upper edge of the thin-wall has less stiffness than the wall's bottom edge. However, the deflection diminishes gradually along the length of the wall towards the bottom edge, which retains its stiffness as it is fixed by the bulk base material. Therefore, it is observed that the wall thickness is smaller at the free top edge and slightly increases towards the fixed bottom edge of the wall. On the other hand, residual stresses generated due to the plastic deformation cause bending of the thin-wall and also affect its surface quality, geometrical accuracy, and performance life. Removing these residual stresses need to conduct post processing treatments such as heat treatment processes which leading to increase the production time and cost as well (Jiang et al., 2018; Hrițuc et al., 2023).

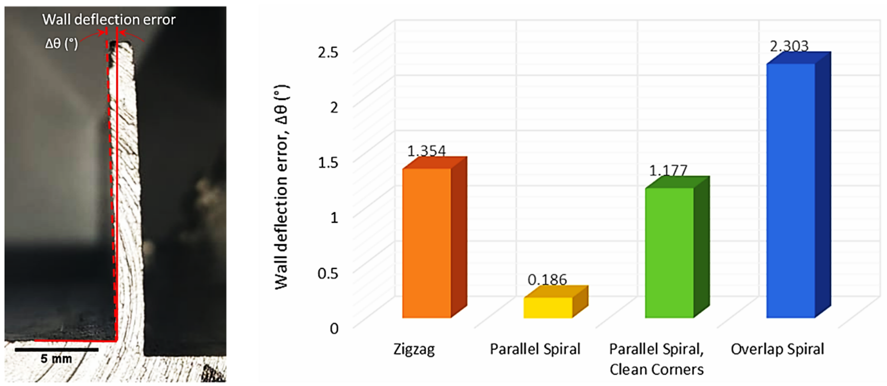
Figure 8 Schematic of thin-wall deflection mechanism during milling of thin-walled parts (see online version for colours)



In Figure 9(a), it illustrates the surface micrograph of the deflected thin-wall obtained after the milling process. It is obvious that higher deflection occurs at the upper part of the thin-wall. Errors of thin-wall deflection at each milling strategy used are presented in Figure 9(b). Minimum thin-wall deflection is obtained when milling using parallel spiral strategy with an error of 0.186°. In contrast, overlap spiral strategy resulted in the largest deflection of the thin-wall as its deflection error reaches 2.303°. The low-stiffness of thin-walled parts makes the milling strategy plays an important role in reducing the machining deformation. In particular, during the milling process, the workpiece distorts due to the milling force and the thin-wall's thickness is gradually reduced in machined layers to remove material as long as the cutting tool penetrates into the workpiece causing vibration. As a result, the thin-wall may deflect under the cutting force and vibrations which negatively affects the geometry dimensions and the machined surface quality

(Kurpiel et al., 2023). Hence, it can be stated that the milling strategy significantly affects the thin-walled part's stiffness in relation to the machine vibration.

Figure 9 (a) Surface micrograph of thin-wall deflection error (b) Results of thin-wall deflection errors at different milling strategy (see online version for colours)



(a) (b)

Figure 10 Variation of thin-wall thickness along its depth for corresponding milling strategy (see online version for colours)

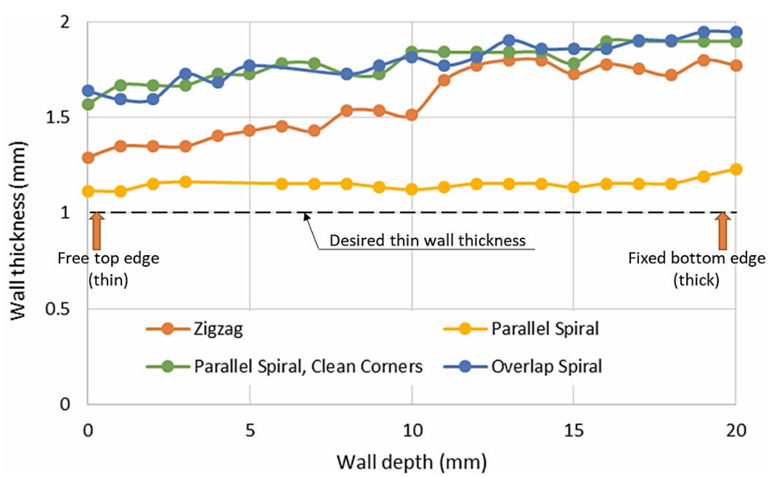


Figure 10 compares how the thin-wall thickness varies along its length for various milling strategies. From the graph, it clearly shows the variation in the thickness of thin-wall as it is smaller and its values are closer to the desired thin-wall thickness at the upper free part of the wall. With the further progress of the milling process, the thickness of the thin-wall significantly increases towards its fixed bottom end. It is ascribed to the higher in-situ thin-wall deflection as the thin-wall's stiffness is less at the free top edge than its base, which is fixed firmly, obstructing the milling process at the bottom end of the wall. Moreover, the wear development of the used end mill tool during milling changes the outer diameter of the tool and notably increases the thickness of the thin-wall. It is also concluded that parallel spiral strategy (gives the less wall deflection error) produces the best thickness of the thin-wall with minimum error of the thickness is about 0.23 mm. However, the other three strategies produce thicker thin-wall than the target thickness with error reaches to 0.95 mm. For all the applied milling strategies, the thickness errors are smallest at the top of the wall, where the wall flexibility declines.

4 Conclusions

This study presents a comparative scheme for different milling strategies during the end milling of thin-walled aluminium parts to evaluate the process's effectiveness in terms of machining time, surface roughness, and thin-wall deformation. Four milling strategies: parallel spiral, zigzag, parallel spiral with clean corner, and overlap spiral, are applied using MasterCAM software. The comparison findings indicate that choosing the appropriate milling strategy is crucial for enhancing the machining performance. According to the results obtained, it is found that the parallel spiral is the best milling strategy amongst the other strategies as it achieves the most accurate thin-wall with minimum surface roughness, wall deflection error, and thickness error with values of 0.1982 mm, 0.186°, and 0.23 mm, respectively. However, parallel spiral ranks as the third strategy in the machining time resulted. In contrary, although the overlap spiral strategy takes short machining time, it noticeably produces the worst thin-wall surface and higher wall deformation as well.

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