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ORIGINAL ARTICLE

Thin Wall Manufacturing Improvement using Novel Simultaneous Double-Sided Cutter Milling Technique

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ABSTRACT – Thin-walled parts are commonly used in the aerospace sector. However, there are serious machining challenges, such as deflection, deformation and vibration. The final thin-walled component machining will deteriorate the dimensional accuracy and surface quality. This is due to the vibration and deformation that occurs during flexible milling of thin-walled structures since the workpiece rigidity is lower than the cutting forces of the milling cutter. The gradual reduction of the thin-wall thickness during the end milling process results in significant deflections and deformations due to its low rigidity and low stiffness. In recent years, different approaches have been used to deal with these challenges. This paper presents a new technique for machining thin-walled parts with great accuracy, excellent flatness and straightness properties, and good productivity. The authors have developed a new milling technique using simultaneous double-sided cutter milling, in which synchronized vertical double end milling cutter finishes and machines both thin-wall surfaces simultaneously. This produces lower cutting thrust forces on the walls, as each cutting thrust force cancels out the other. The rotation of the milling machine spindle is transmitted to the double cutters by an in-house double-axis adapter. Surface errors are minimized, flatness and straightness properties are significantly improved, and the thin-wall deflection can be neglected, as shown in our results. The thin wall can be finished in only one pass, and a 50% reduction in machining time can be achieved. In addition, thin-wall flatness is improved about two to three times, compared to the conventional milling procedure.

INTRODUCTION

Monolithic thin-walled components have low rigidity. They are one-piece designed to be used widely in the aerospace industry to replace many assembled parts [1]. The complex design and tight dimensional tolerances of aerospace parts pose dramatic challenges to the producer. As shown in Figure 1, thin-walled parts made of aluminium alloys are used widely in the aerospace industry. The aerospace industry needs monolithic thin-walled components to manufacture sections of the aircraft fuselage, wings, door frame, and engine blades. Monolithic parts are machined from a single block of the workpiece to their final shape. Monolithic components are preferred over the traditional riveted-welded parts, due to the high setup cost and lengthy production duration associated with the latter [2].

In cutting processes, especially milling machining, these thin-walled components deform easily because of their low rigidity and stiffness. Machining plates or structures, including thin-walled, is very complicated at the end milling process because of the gradual reduction of their thickness during the milling process [1],[3]. The varying milling forces periodically excite flexible thin-walled structures dynamically and statically, resulting in significant deflections and deformations; thus, the end milling process is considered complicated [4]. In addition, compared to traditional structures, the overall machining costs of thin-walled monolithic parts are reduced, they are light in weight and the strength to weight ratio is high. Undercutting forces thin-wall milling deflects and deforms the skinny features contained in the plate structure. These deformations and deflections cause unwanted material and errors in surface dimensions, requiring subsequent finishing [4]-[6]. In general, milling several thin-walled rib and flange sections produces monolithic parts and components. Thin-walled components must have excellent flatness and straightness properties for high-quality aerospace products [7].

It is well known that, due to the thin wall's low rigidity and stiffness, milling forces will deform and deflect the thin wall in the opposite direction during the machining process. This will cause errors in straightness, flatness, and surface dimensions that will affect the accuracy of the component. To solve this major problem, many post-milling operations, such as a final "float" cut and repetitive feeding to achieve the tolerances required by the component designer, are adopted [8],[9]. Current thin-wall machining techniques are inefficient and complicated in terms of productivity. The geometrical error produced during thin-wall milling is shown in Figure 2 [10],[11]. Material ABCD is required to be removed. However, under the effect of machining forces, the low rigidity thin-walled structure is deflected, resulting in cutting away material A'BCD. When the cutter travels away from the milled zone, elastic recovery of the wall occurs, and material C'CD remains uncut. This well-known problem appears in thin-wall milling components [10],[11]. This phenomenon causes the wall shape to be thinner at the bottom and thicker at the top. Researchers proposed several

approaches, such as trial and error or feeding repetitive techniques to minimize these thin-wall straightness errors. However, these approaches may cause longer machining time and higher production costs [10],[11].
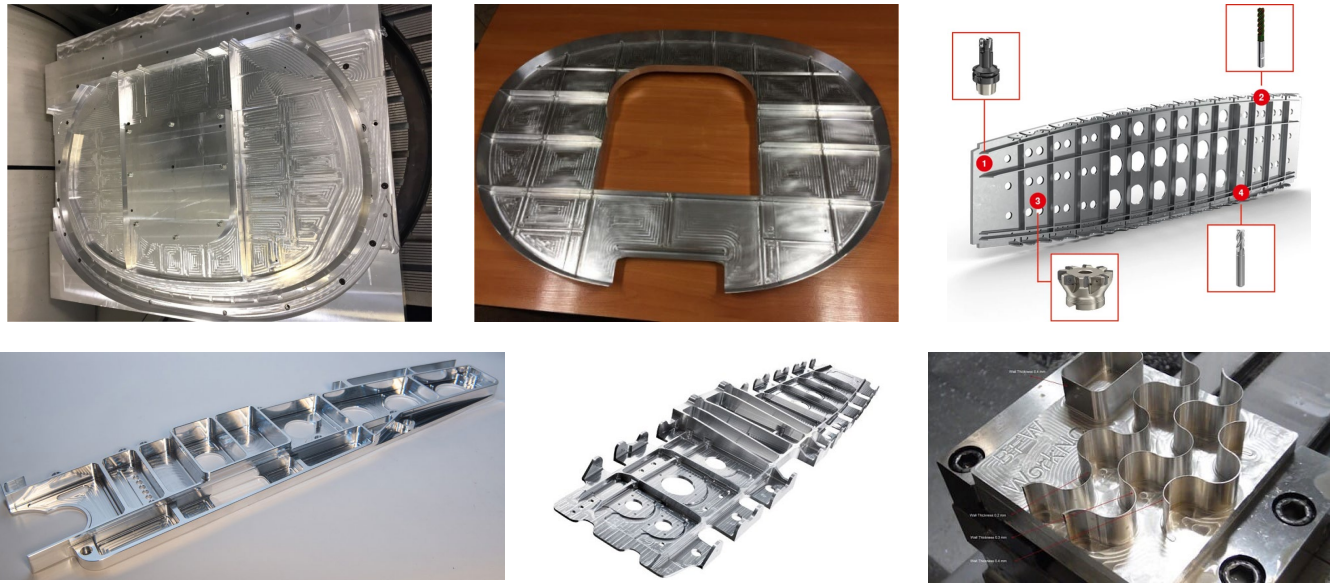
**Figure 1.** Aluminum alloy thin wall parts used in the aerospace industry [12]-[17].
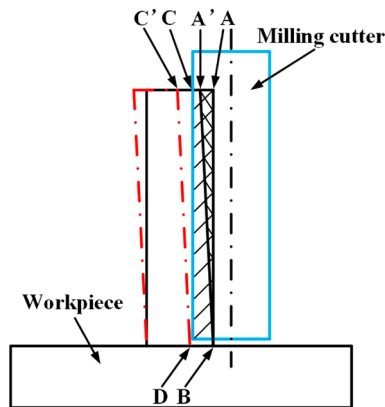
**Figure 2.** Errors in thin wall vertical end milling [10], [11].

Another serious emerging problem limiting productivity is the chatter regeneration caused by thin-wall flexibility. Stable forced and unstable chatter vibrations cause natural structural frequencies to be excited in the workpiece during the intermittent engagement of the workpiece with the cutter which could harm the surface finish of the precision machining. A lot of research in the area of flexible part deformation in milling operations has been executed [18]-[20]. Mori et al. in 2011 [21] proposed a novel technique to machine flexible plates with good productivity and precision, as shown in Figure 3. Steel plates are machined conventionally to a precision finish using electromagnetic chucks in the face milling method. However, when these steel plates are clamped to fit the chuck surfaces, they deform. Improving the flatness of these flexible plates is considered problematic. The authors proposed a new technique of double-sided simultaneous milling to resolve the chatter vibrations. Simultaneously finishing with synchronization of single tooth milling cutters on both surfaces, cancelling the thrust forces on both sides. Shamoto et al. in 2010 [22] proposed a new technique to restrain the chatter vibrations. Rotating at different speeds, the simultaneous double-sided milling cutters cancel out the both-sided regenerative effect, as shown in Figure 4. Previous recommendations for gaining better thin-wall straightness during end milling include using climb (up) milling, in which the tool pressure is kept to a minimum. Furthermore, wall stabilization and manual vibration damping can be adopted [23].

Special CNC milling centres were designed and adopted to machine thin-walled parts for the aerospace industry [24]-[26]. The process is called mirror milling, as these centres are built with two symmetrical heads. To reduce the deflection and ensure the support of the part, the first head that holds the cutter contacts the workpiece perpendicularly, and the second head is synchronized to support and follow the cutter that is fixed on the first machining head. This approach reduces vibration, chatter, and part deflection [24]-[26]. The machined surface quality with support is significantly better than that without support. It can be proven that, at different positions in the mirror milling process, the support head can improve the surface quality of the workpiece and effectively suppress the milling vibration [24]. Other modern techniques

to support thin-walled parts during machining are flexible work holdings. These devices, based on FEM studies, support thin-wall positions at the predicted optimal locations.


| (a) double sided milling machine | (b) workpiece machined with forced chatter |
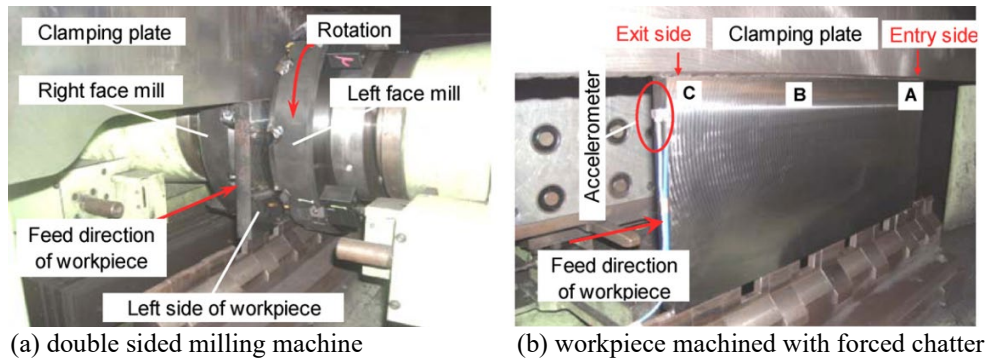
Figure 3. Experimental setup of the simultaneous double-sided milling technique [21].

| (a) double sided milling machine and process | (b) thin workpiece machined with chatter |
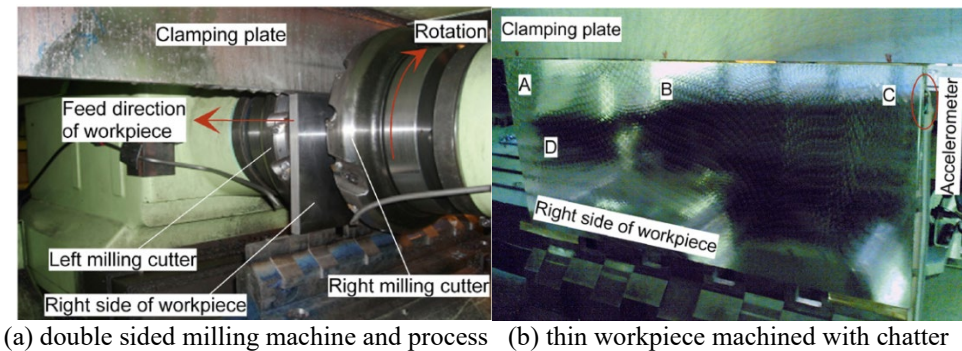
Figure 4. Experimental setup of the simultaneous double-sided milling technique with different rotational speeds [22].

Figure 5 illustrates Innoclamp® [27], a commercial example of flexible holdings. Innoclamp is designed to compensate all over the workpiece for the cutting energy. At the most flexible positions of the thin-walled parts, the supports are applied to the optimal locations defined by simulations. The work holding behaviour can change depending on the operation because the system usually has embedded sensors [27].
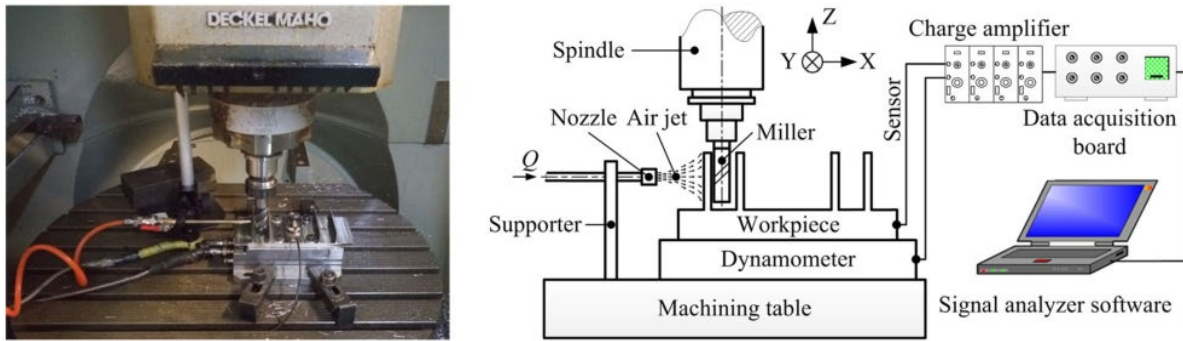
Liu et al. [28] suggested a novel approach to reduce the deflection on the thin-walled part by using an air jet, as shown in Figure 6. In the mirror milling criteria, the air jet is synchronized to follow the cutting tool fixed in the machining head, acting as cutting force support by impacting one side of the thin wall. Its influence was evaluated by final roughness data, thickness, cutting forces, and vibration. Air jet assistance milling experiments proved that both machined surface quality and thickness error were improved, and the vibration of the thin-walled part was reduced by up to 47%. Jixiong Fei et al. [29] proposed a new method, using a supporting head on the back surface of the thin-walled part localized at the projection area of the workpiece-tool cutting zone. During the cutting operation, the fixture head is synchronized to move with the end milling cutter.
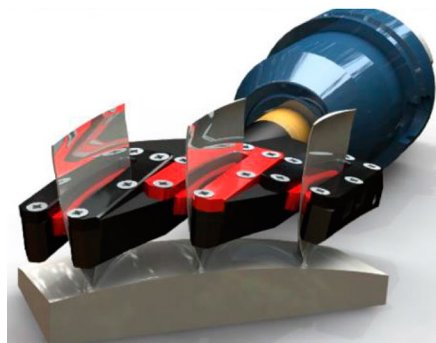
Figure 5. Innoclamp® holding system[27].

Wang et al. [30] studied the application of a unique material having a phase change to prepare flexible fixtures by adopting a low-melting-point alloy (LMPA). The study focused on the challenge to clamp complex thin-walled parts. The LMPA was warmed to its melting point of 70 °C and cast in the cavity between a rigid fixture and the workpiece to create a solid structure or frame with fixture among the workpiece, fixture, and LMPA. During machining, the rigidity of the whole component was increased due to the use of the LMPA. The machining accuracy was significantly improved. The

vibrations and deformation caused by the machining forces also decreased. After finishing the machining operation, the LMPA was melted and no influence was observed on the part quality.

Figure 6. Experimental setup for milling thin wall workpiece with air-jet assistance [28].

Kolluru et al. [31] suggested a novel damping approach to reduce milling vibrations by applying a flexible, thin layer fixed with a distributed detached weight, joined with a layer of viscoelastic material. They concluded that the machining vibrations were reduced by a factor of four. Kolluru and Axinte [32] reported applying a new ancillary system to minimize thin-wall vibrations at milling operations. The device is pre-tensioned and articulated by the torsion springs. It will not change the dynamic structural characteristics, can be used for any flexible part shape, and is lightweight. Recently, Zhang [33] proposed a unique idea of submerging the thin-walled part in viscous liquid during the machining process. Compared to the dry-cut conditions, the corresponding stability limit was significantly improved, and the chatter was successfully mitigated

Baohai Wu et al. [34] suggested a novel suppression process to minimize the deflection errors in thin-walled aero-engine blades, based on multipoint auxiliary support. This approach is much more suitable and versatile than other additional supports for spiral finishing in milling operations. In addition, a mechanism of additional multipoint support was manufactured and designed for experiments that can be rotated to adapt and support blades with various torsional angles. The average deflection of the thin-walled aero-engine blades reduced from 45.9 to 24.4 µm. Thus, multipoint auxiliary support can effectively improve the machining accuracy and reduce the deflection errors in the blade.

To control the milling deformation of flexible components, the development of other methods and techniques have been achieved. These include milling path planning [35],[36], online compensation [37], electromagnetic induction [38], damping method [31],[39],[40], fixtures [41],[42],[43],[44], a waterfall machining technique developed by Boeing Manufacturing R&D group [45] and a sacrificial structures method [46].

In summary, based on the many thin-walled component machining related studies performed in the last three decades using a single cutter, chatter vibrations and cutting forces harmed the integrity of the surface and the accuracy of the dimensions of the thin-walled structures due to their low rigidity and low stiffness [47]-[49].

Thus, this research proposed, for the first time, a simultaneous double-sided end cutter milling technique using two identical end milling cutters. The cutters having equal rotational speeds and directions, utilize a classical milling machine by adopting a developed milling adapter. A uniform thin wall with high dimensional accuracy, good surface finish with low chatter and almost zero deflection can be achieved because the same cutting forces occur on both wall sides; thus each force cancels out the other [50],[33].

EXPERIMENTAL WORK

Simultaneous double-sided end cutter milling is designed for a particular purpose, to machine low rigidity, thin-walled structural components adopting two identical end mill cutters having the same tool characteristics. It implements simultaneous machining by adopting dual spindle rotation using a special adapter to remove metal from both sides of the thin wall. The required thin-walled part is simultaneously machined by right and left milling end cutters on both sides. The same cutting forces apply on both sides of the thin wall simultaneously, thus controlling the thin-wall deflection and minimizing the forced chatter vibrations. Figure 7 illustrates the principles of this new technique. A special adapter is used to synchronize the spindles. The left and right spindles are driven from the main milling machine spindle. Before starting the milling process, the right and left outer diameter cutters are set 1 mm apart. Both cutters have the same rotational velocity and direction, and simultaneously touch the 2 mm thickness previously machined thin-wall.

The direction of rotation is clockwise for both cutters; thus, side A (left side) produces a down milling cut, and side B (right side) an up milling cut. A BT40 taper head drives the two cutters by a special adapter (twin drill head, model 2D43-5100APV, made by Sugino Machine Limited, Japan) as shown in Figure 8. The adapter causes the two cutters to be fed simultaneously into the workpiece. The unique adapter can adjust the centre distance of spindles to any required position according to the desired wall thickness, which in this study was 1 mm. An arrangement of aligned planetary gears inside the adapter transmits the rotational movement from the spindle of the main milling machine through the central gear to the double-sided cutter spindles. Two machining tests were performed to obtain the 1 mm thickness of the thin-wall, one using the traditional single cutter milling method and the other using the new double-sided cutter milling technique. A 3-axis classical milling machine was used to conduct the experiments. The workpiece part was made from

aluminium alloy 2024-T531 pre-machined to 80 mm length, 30 mm wall height, and 2 mm wall thickness, as shown in Figure 9.
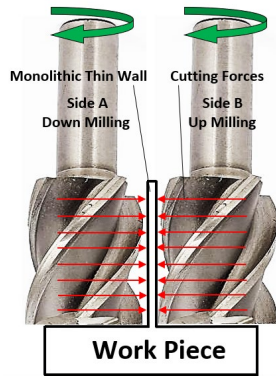

Figure 7. Acting cutting forces in the double milling process.

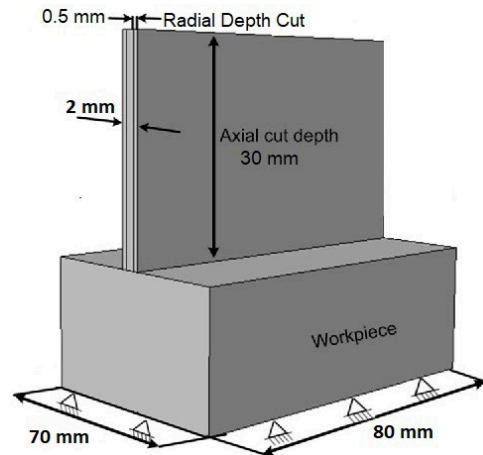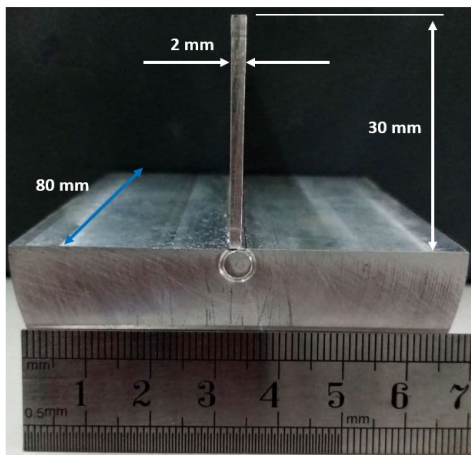**Figure 8.** The unique adapter used in the experiments.

Figure 9. Pre-machined 2024-T351 alloy to be prepared for single and double cutter milling technique.

The chemical properties of aluminium 2024-T351 are illustrated in Table 1, and the machining conditions are described in Table 2. The specifications of the two cutters are presented in Table 3 and Figure 10. Using both single and double-sided cutter milling techniques, the thickness of the wall was machined from 2 mm to 1 mm at a cut depth of 30 mm in the axial direction and a cut depth of 0.5 mm in the radial direction. Two identical HSS end mill cutters with four flutes and 20 mm diameter were adopted in this study. The machined wall accuracy was measured by a Mitutoyo profile projector model PJ-A3000 (made in Japan) as shown in Figure 11 and a Mitutoyo dial gauge of 0.01 mm accuracy (made in Japan) with a measuring step of 0.5 mm in the vertical direction. The cutting forces were measured by a Kistler Dynamometer (made in Germany), and the surface roughness was measured by a PosiTector model KITSTD (made in the USA).

Table 1. Chemical composition of AA 2024 T351.

Element	Fe	Mn	Si	Cr	Mg	Zn	Cu	Ti	Al
Content (wt.%)	0.41	0.32	0.4	0.06	1.32	0.21	4.1	0.13	Rem.

Table 2. Machining conditions.

Cutting condition	Radial depth of cut (mm)	Axial depth of cut (mm)	Feed rate (mm/min.)	Spindle speed (RPM)
Dry	0.5	30	25	1800

Table 3. Cutting tool specifications.

Tool Material	HSS
Tool Diameter (mm)	24
Tool length (mm)	35
Shank Diameter (mm)	10
Clearance angle (º)	15
Helix angle (º)	45
Rake angle (º)	12
Number of flutes	4
Shank Length (mm)	40

Figure 10. HSS cutter is used in single and double cutter milling techniques.

**Figure 11.** Mitutoyo profile projector for thin wall flatness measurement.

RESULTS AND DISCUSSION

The developed adapter fixture conducted simultaneous milling by the double-sided cutter milling technique to perform thin-wall milling. Figure 12 illustrates the surface flatness errors of the produced 1 mm thin-wall for double-sided and single cutter milling techniques at locations of 5mm, 40 mm and 75 mm. In the single cutter milling method, it is observable that the surface flatness error has variable values across the wall height, caused by the deflection of the wall during the milling operation producing an inconsistency in the depth of cut. At the top of the wall, the surface errors are more visible and decrease gradually towards the bottom, indicating the stiffness of the wall.
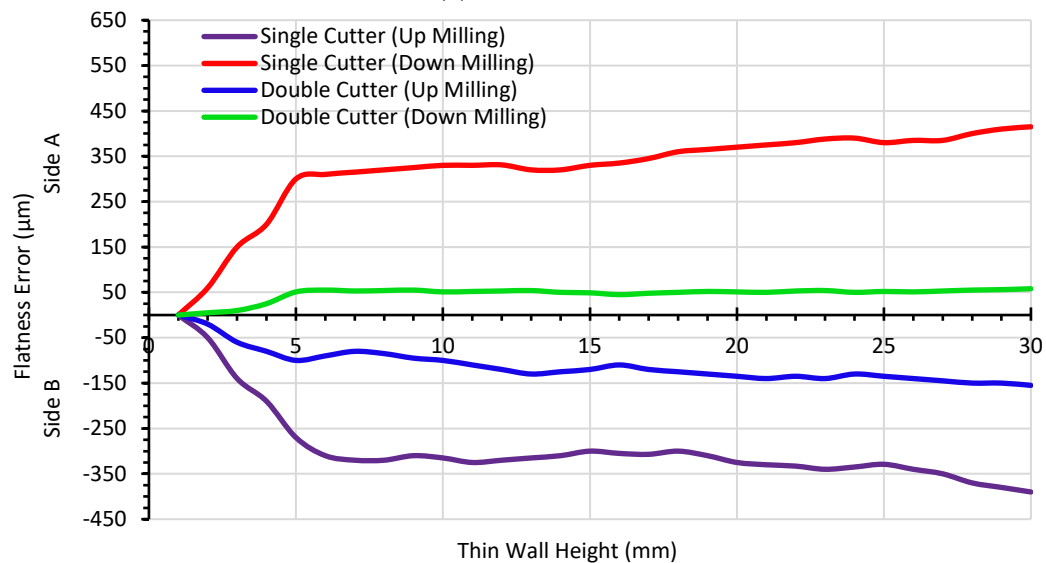
The double-sided cutter milling technique showed better wall thickness consistency, with a minor error that can be neglected. In the double-sided cutter milling technique, up milling showed slightly more flatness error than down milling, especially at the top of the wall where the vibrations and deflections are more pronounced than at the bottom surface.

Since the wall flexibility increases at the top surface of the wall, surface flatness errors were higher at wall height h = 30 mm than at h = 1 mm for the single cutter milling technique. As shown in Figure 13(a), the wall thickness appears to be thicker at the top than at the bottom. During machining, the wall flexibility will cause a larger surface error. This is attributed to the fact that its top portion is unconstrained and free to deflect under the action of the cutting forces, while the inverted cantilever is fixed at its bottom portion. Also, the material at the top end remains uncut because the lower stiffness value leads to increased deflection of free ends [51],[52].

(a) at X = 5 mm
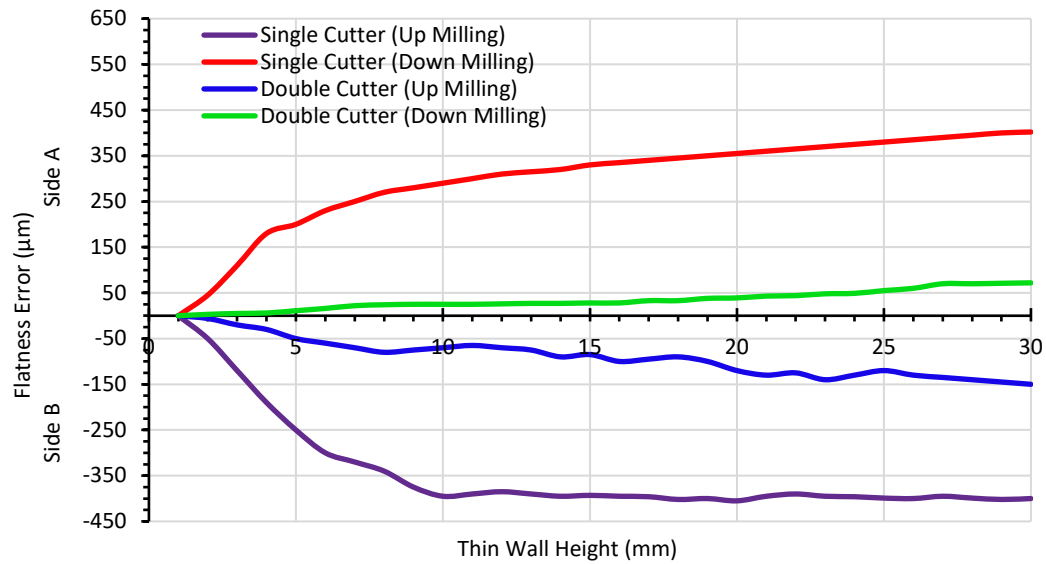
(b) at X = 40 mm

(c) at X = 75 mm

Figure 12. Surface flatness errors between single and double cutter techniques at three different locations.
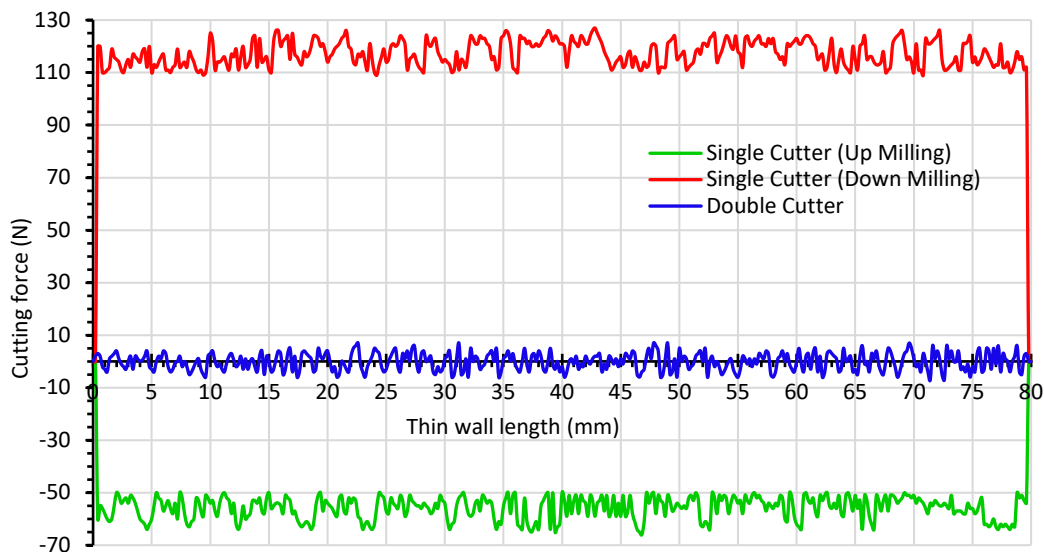
In the double-sided cutter milling technique, at the starting stage of machining, the surface error pattern is affected by the wall deflection to the rest of the wall surface. When the double-sided cutters exit the workpiece, the ending surfaces are subjected to maximum deformations causing the surface errors to be higher than the errors at the starting stage. In the double-sided cutter milling technique, all regions of the machined part had consistent wall thickness from the bottom of the wall to the top, as shown in Figure 13(b).

(a)   (b)
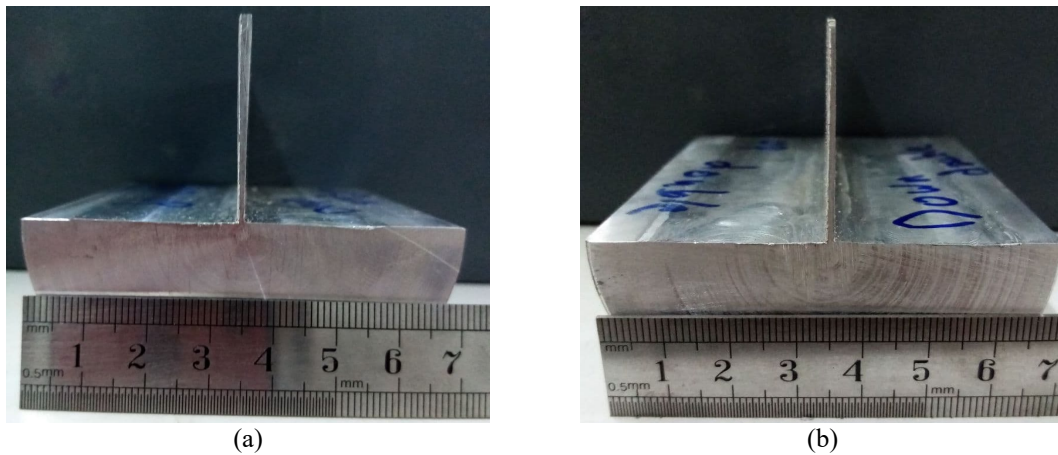
Figure 13. Wall straightness after milling with (a) single and (b) double cutter technique.

The double-sided cutter milling technique revealed better dimensional surface errors than the single cutter milling method due to fewer deflections of the thin wall caused by the cancellation of the cutting forces on both sides. The double-sided cutter milling technique presented a machining process stability, as a smooth machined surface with less chatter was achieved. In addition, two to three times improvement in surface flatness was revealed by this technique. Milling forces will induce part deformation, significantly influencing the dimension errors. Machining or initial-induced residual stress will cause a distortion that will influence the shape errors. Part distortion/deformation is the essential source causing part errors during thin-wall machining [23]. The deflection of the thin-walled part induced by the forces of cutting can be predicted precisely by analytical or numerical procedures. However, an effective way for predicting the induced distortion by the residual stress after milling is unavailable. The coupling relationship between milling-induced and initial stress is unclear [23].

Figure 14 indicates double-sided cutter milling and single cutter milling techniques force magnitudes in the Fx direction and indicates that cutting forces were minimum for the double-sided cutter milling technique. Higher cutting forces were presented in the single cutter method, especially for down milling. With the double-sided cutter milling technique, from the starting stage (at x = 0 mm) until the end stage (at x = 80 mm), the cutting force was almost zero. This is attributed to the equal forces and pressures applied on both wall sides simultaneously. Therefore, wall deflection can be controlled in this method.

Figure 14. Fx direction cutting force plot for single and double cutter technique.

In the single cutter milling method (up milling), the dynamometer sensor presents negative force values because of the opposite side cutting action of the single cutter. The dynamometer senses these negative values as the deflection moves to the other side. Down milling forces were revealed to be higher than the up milling forces. This is attributed to the decrease in the specific cutting pressure for up milling from down milling that is higher for thick chips than for thin

chips. This can be explained by the 'squeeze' effect. As the cutting starts in up milling, infinitely small chip thickness is encountered by the cutter, and thus the surface will be squeezed by the cutting edge, which has already been cut by the previous tooth [53]. This procedure continues until another actual cut starts. There is no squeezing effect in down milling because the tool edge is already cutting when the chip thickness becomes smaller, and the cut begins with a finite chip thickness [54]. At the beginning of the cut, the chip thickness is at its maximum value, causing the specific cutting pressure in down milling to increase for thicker chips. This means that the cutting edge encounters the thickest chip first whenever it makes a fresh start.

On the other hand, in up milling, when the cutter has already been cutting for some time, the edge reaches the thickest chip. Therefore, for this case, when a start has already been made, the specific cutting pressure is smaller for the same chip thickness [53]. Rohlke also noticed this issue [55] and tried to correlate the effect of an increase in rake angle with a similar effect of an 'existing' start. Thus, in up milling, the mean and specific cutting pressures are lower than in down milling. The increase is lower for low chip thicknesses and it becomes more effective for high chip thicknesses. In down milling, therefore, more energy would be needed for spindle rotation. For down milling operations, although the energy required is reduced for the feed motor, higher energy machines would be necessary [53][54].

The thin-walled plate deformations increase with higher milling forces in the end milling process. The deformations might go beyond the small deformations range if the load is continually increased, seriously affecting the machined part's quality and accuracy. Accordingly, in thin-walled end milling, a selection of suitable cutting conditions should be made to ensure that the cutting force limits are not exceeded, providing that the deflections of thin-walled parts are to a definite range [56]. Thus, it can secure the quality and accuracy of the thin-walled workpiece. The deflections have standard rules; the deflections in thin-walled parts increase gradually from bottom to top. When the cutter's edge contacts a specific position of a thin-walled part, maximum deflections of angular free points near the cutter's position. Hence, in thin-wall end milling, the part induces more significant deflections when the wall is higher. The quality and accuracy of the thin-walled workpieces are more difficult to control and are poorer [1].

Few cutter marks and higher surface roughness are obtained by the double-sided cutter milling technique as observed from the photos. Severe chatter vibration is indicated and severe cutter marks and surface waviness is apparent from the single cutter milling method. The results indicate an enhancement in machined part accuracy using the double-sided cutter milling technique. Furthermore, improved vibration and deflection control can be achieved with machining time (a reduction of half the machining time is achieved).

Surface Roughness

Non-homogenous surface finish is produced on the final machined parts, and different surface qualities are shown in several zones. Surface quality calculations can only be conducted on the homogenous zones, the roughness measurement was done on three zones. The first at the starting stage, the second at the middle stage, and the third at the end stage. Figure 15 shows the surface roughness plot for both cases. The measurements were taken in three-zone positions (at x=5 mm, x=40 mm, and x=75 mm), at the height of h = 15 to 30 mm. Double-sided cutter down milling showed the best results of surface quality, the roughest surface was observed with single cutter up milling. Under the action of cutting forces, the inverted cantilever workpiece undergoes cyclic deflections. This was due to the repeated cutter teeth engagement and disengagement with the work part and results in non-uniform material removal and an unevenly finished surface [11].
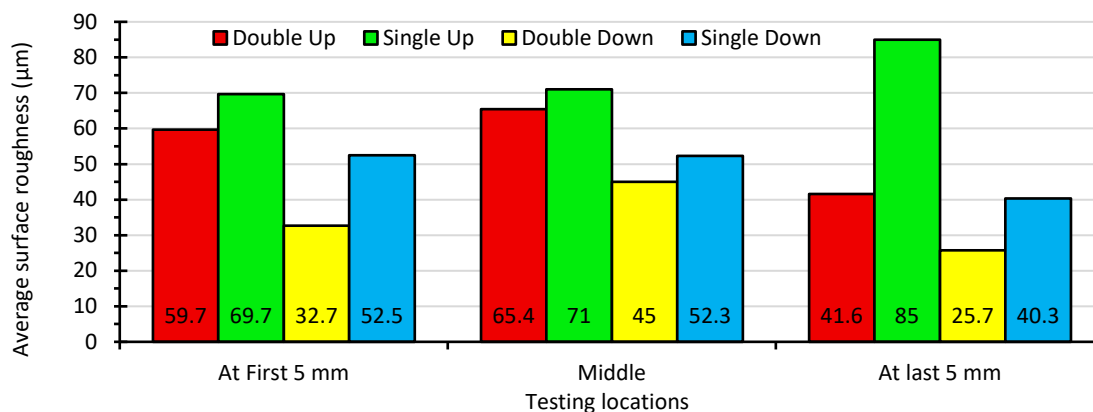
Figure 15. Thin wall average surface roughness measurements at three testing locations.

During the thin-wall milling operation, the surface roughness is directly related to the cutting forces [57]. Other factors, such as wall deflection and contact width/length, were set to affect the surface quality. The thickness of the undeformed chip varies as the contact width/length varies. This increases the variation in cutting force, leading to poorer surface quality. Under the condition of the high depth of axial cut, the deflection of the low rigidity thin-walled part causes irregular contact between the workpiece and tool, resulting in variation of chatter and cutting forces. The machined thin-walled surface quality is severely affected [58].

CONCLUSION

An efficient and precise new milling technique to machine thin-walled structures was developed in this research by adopting a simultaneous double-sided cutter milling technique. A synchronization procedure of identical milling cutters is conducted to cancel out the cutting thrust forces on both wall sides. This research proposed a new milling technique to effectively machine low rigidity thin-walled structure components. Improved productivity is achieved using the double-sided cutter milling technique with a machining time reduction of 50% compared to the single cutter milling method. Stable thin-wall machining conditions are achieved with the double-sided cutter milling technique. The double-sided cutter milling technique indicated reduced cutting force acting on both walls, with fewer cutting marks and consistent surface roughness. Surface flatness error is dramatically reduced, and the double-sided cutter milling technique achieves excellent wall deflection control. Performing the simultaneous double-sided cutter milling technique using two identical cutters is improved by the developed double-sided cutter adapter for machining thin-walled parts with excellent stability and accuracy. The proposed approach improves the flatness of the thin wall by a factor of two to three, compared to the single cutter milling method.

ACKNOWLEDGEMENT

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