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A TWO-STEP APPROACH TO MILLING THIN WALLS ENCOMPASSING CONSTANT CUTTING FORCE AND PASSIVE DAMPING

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Abstract. *Milling of thin walls is a challenge that is usually overcome by means of restricting product geometry in a way that allows for parts to be machined with strategies that are similar to those used for conventional rigid parts. This results in heavier parts and therefore less efficient structures, which puts forward an opportunity for improvement in finding new methods to produce lighter and more flexible components. Usual strategies suggested in literature are based on alternating the sides of the wall being machined in a way that the structure is kept as rigid as possible during the process. This work proposes a strategy for machining thin walls that takes advantage of the possibility of producing constant cutting forces in milling by means of specific cutting depths and helical cutters. In order to compensate for the low damping of these walls, a passive damping method is also proposed which, when combined to the constant cutting force approach, allows for machining time to be reduced when compared to usual strategies. The procedure is described and two different test conditions are conducted to investigate the actual performance of the proposed strategy. Results indicate that the strategy is feasible and is able to produce parts with acceptable roughness and dimensional deviations, when applications in aircraft components are considered.*

Keywords: *milling, aluminum, thin wall, constant cutting force, strategy*

1. INTRODUCTION

Milling is a machining process in which the cutting edge of a tool removes material through a combination of rotational and translational motion. A specific category of this process is known as end milling, in which the cutter removes material using the entire geometrical envelope described by its rotating motion. Several types of end milling cutters are available commercially for a wide range of applications. Typical tools used to produce 90° profiles in several applications are square-shoulder (cylindrical) end mills. One of these applications is manufacturing of aerostructures in which thin walls are used as reinforcing ribs (Fig. 2).

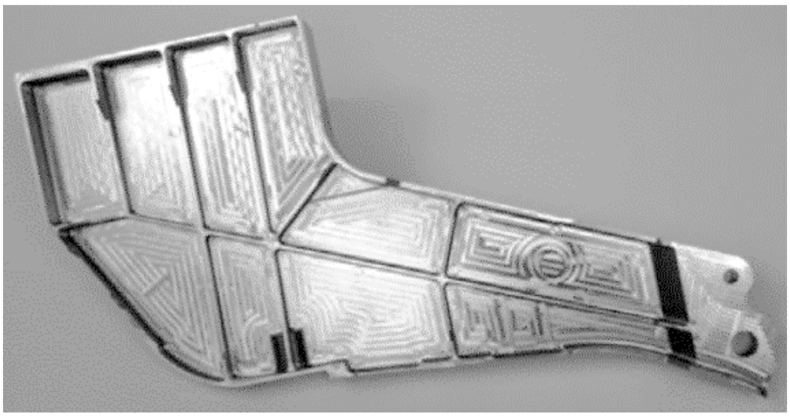


Figure 1. Typical aerostructure with thin features: a lightweight alloy arm. Source: Munoa *et al*. (2016).

Munoa *et al*. (2016) presented a comprehensive review of current trends in machining instability research. In the review, they enumerated reasons for which this topic shall continue demanding research in the future, which can be classified into two categories: 1-machining technology evolution and 2-manufacturing of flexible parts. The driver for the second point is the fact that increased component performance in the mobility industry is, generally, a synonym of reduced weight. Reducing weight in turn has a direct effect on the rigidity of components, making them more prone to instability during machining.

The industrial scenario, therefore, requires the use of techniques that allow more flexible parts to be manufactured with adequate costs and minimal impact on the current factory infrastructure. Several methods have been proposed in literature for aiding milling of thin walls, such as stability lobe theory (Altintas and Budak, 1995; Budak *et al.*, 2012) and normal modes avoidance methods (Bolsunovskiy *et al.* 2013, Mundim and Borille, 2017). These methods, however, demand additional competences in numerical and experimental structural analysis to be applied in real situations, while also being generally unfeasible for very complex structures due to the necessary computational power. Other strategies based on alternating sides during finishing in a stepwise manner (Coromant, 2005) are not effective in all situations since the dynamic behavior of the part is not taken into account, thus allowing instability to take place due to excessive vibrations, as observed in the work of Popma (2010).

This paper aims at proposing a technique for milling thin walls based on 1-overlapping of cutting edges in helical end milling (constant force strategy) combined to 2-a finishing pass under external passive damping. The theoretical basis for the proposed strategy is exposed in the next section and experimental results in milling of an aeronautical grade aluminum alloy (AA 7050 T7451) are exposed in the experimental trials section. A discussion on the dynamic stability of the cutting process as well as part quality are also part of the same section.

2. A STRATEGY COMBINING CONSTANT MILLING FORCE AND PASSIVE DAMPING

Several geometrical characteristics are found in commercial end milling tools, some of which are depicted in Fig. 2. For the purpose of this work helix angle (γ), diameter (D) and the number of teeth (N_t) are of prime importance. By taking advantage of the helical geometry of the cutter, Tlusty (2000) presents a result that can be exploited in order to achieve constant cutting forces in milling, as described by Eq. (1). This is attained at specific axial cutting depths (a_{p_const}) when the delay angle (χ) of the engaged tool equals the tooth pitch angle (ϕ_p). The delay angle, also known as the edge-spread angle, is described as the angular distance over which the cutting edge is in contact with the workpiece being cut. In this situation, the same edge length is engaged at any instant, despite radial cutting depth (Fig. 3). It should be noted that not only at a_{p_const} forces will be constant, but also at integer multiples of this value. Also, it is assumed that the cutter in use has enough length of cut to achieve depths as high as the calculated a_{p_const} values.

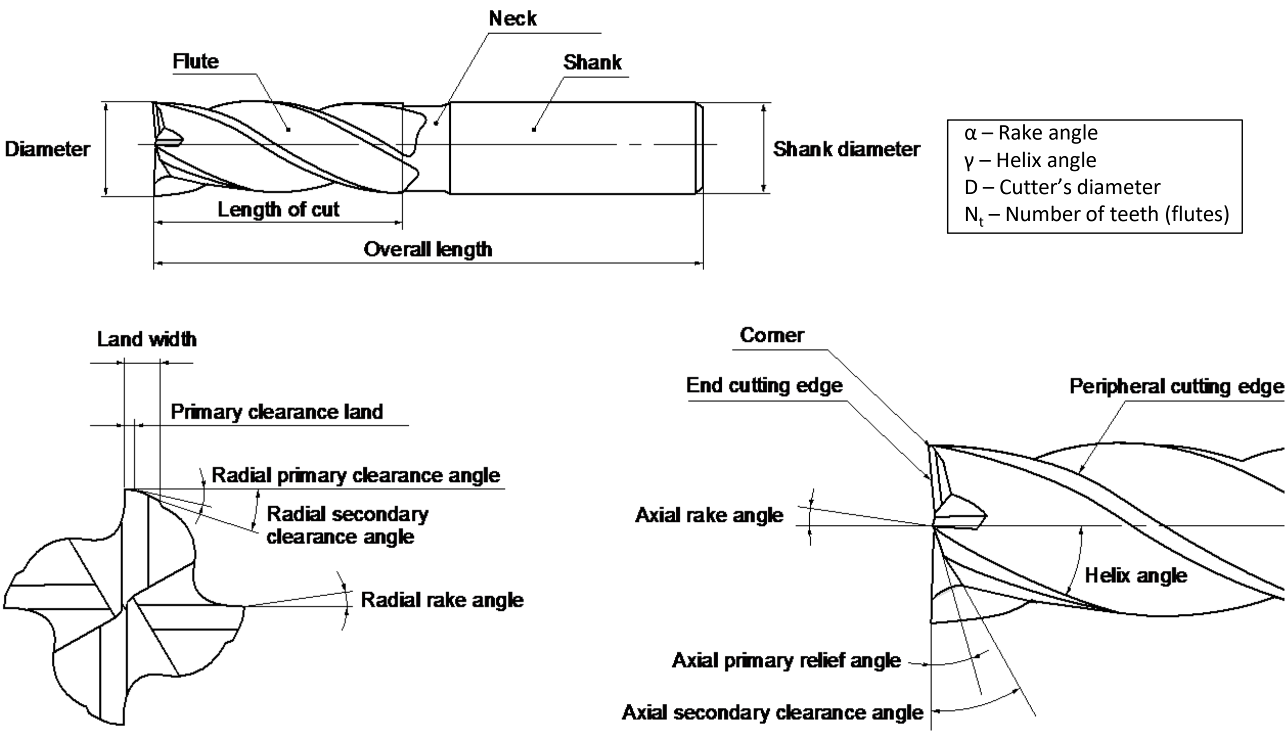


Figure 2. Cylindrical (square-shoulder) end mill geometry. Source: Mitsubishi (2013).

$$a_{p\_const} = \frac{D \cdot \phi_p}{2 \cdot \tan\gamma} \tag{1}$$

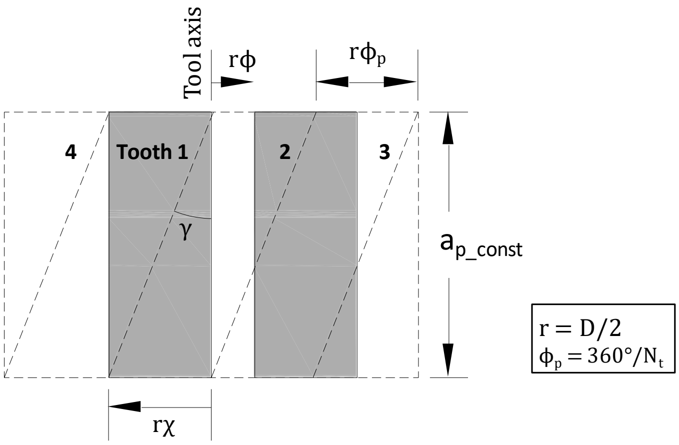


Figure 3. If the delay angle (χ) is equal to the pitch angle (ϕ_p), the same length of cutting edge is engaged at all times (gray boxes), making the resultant force constant for this axial depth of cut. Adapted from Schmitz & Smith (2009).

Considering usual commercial cutting tool geometries for aluminum end milling, a general analysis of Eq. (1) can be conducted. Most commonly, two to four-fluted cutters are available for machining aluminum alloys due to the larger chip removal volume attained. Additionally, helix angles ranging from 25 to 45 degrees are also more commonly available for these applications (Coromant, 2010; Taegutec, 2012). From this information, one can derive the usual application ranges where it is possible to exploit constant cutting forces from these tools (Fig. 4). From these results, it can be noted that constant cutting force can be reached with lower cutting depths when cutters with more flutes, smaller diameters, and higher helix angles are adopted.

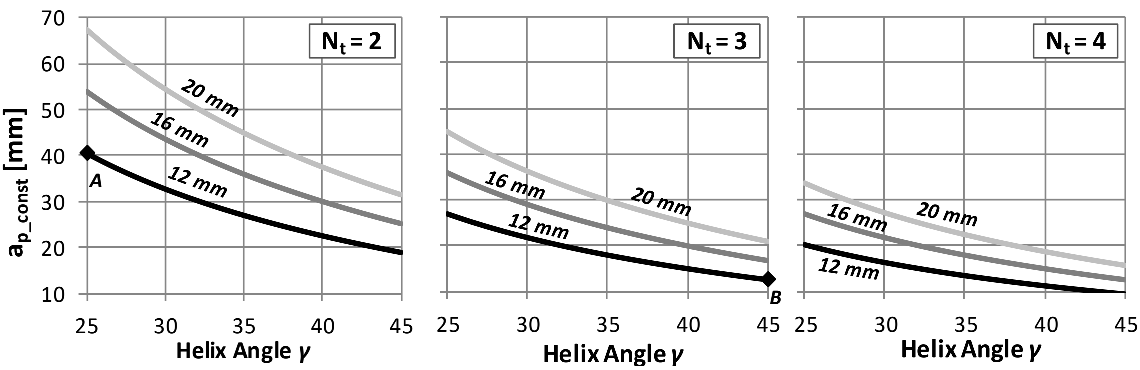


Figure 4. Necessary cutting depth for constant force milling for selected commercial range aluminum end mills. Points A and B indicate geometries tested in this study. Geometry data obtained from Coromant (2010) and Taegutec (2012).

First, since forces acting on the workpiece and cutting tool will be constant, surface formation will always occur at a point different from the programmed value due to deflection. This certainly becomes less of an issue when rigid cutting tools and workpieces are adopted. However, when slender end mills are used along with flexible workpieces, deflections might be a limiting factor. Finally, since axial cutting depths are considerably high, small disturbances during cutting can set off unstable conditions, making the whole process unreliable (Schmitz and Smith, 2009).

When rigid workpieces are machined this technique can be used effectively to finish surfaces, as long as tool deflection is low enough that dimensions are kept within tolerance. However, when milling low rigidity workpieces with this technique, two main issues may arise. First, it should be taken into consideration that, when machining with slender end mills, lower stock should be left for finishing in order to reduce forces and ensure cutting tool stability. This lower stock also reduces workpiece stiffness, making it more prone to undesired deflections and dimensional deviations. This is aggravated by the higher cutting forces expected when an increased axial cutting depth (a_p) is adopted, despite the low radial immersion (a_e).

Due to the plate behavior of the workpiece, deflection is not constant when a constant force is applied at different points along the feed direction. It should be expected, therefore, that different thicknesses will be encountered on the final workpiece due to deflection during machining. As illustrated in Fig. 5, when force is applied to one of the free ends of the thin wall, deflection can be twice as high as that occurring when the same force is applied to the center of the workpiece. A second issue, regarding stability on entrance, must also be taken into consideration. Since a transient force period occurs when the tool enters the cut, this can cause instability, invalidating the constant force strategy.

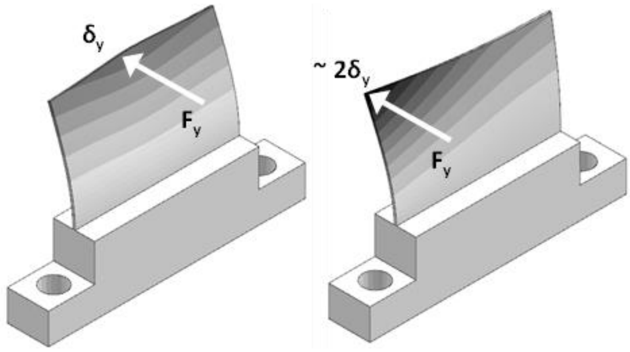


Figure 5. Numerically simulated displacement (δ_y) of a cantilever wall under a load at the center of its span (left) and at the corner edge (right). Static simulation done in Siemens® NX Nastran 11.

Despite the theoretical benefits expected from constant cutting forces, some disadvantages may exist. A constant force being applied on a thin wall during finishing could cause the final product to deflect considerably, causing instability and an undesired final shape. Therefore, a combined strategy is proposed in order to obtain an acceptable geometry in a short amount of time. This combined strategy consists of machining one side (side A in Fig. 6) of the wall to its final dimensions by means of constant cutting force parameters and then machining the opposite side (side B in Fig. 6) with a low force strategy and passive damping. Passive damping in this case becomes necessary since the wall will be considerably more flexible during machining than it was with usual waterline strategies (*cf.* Coromant, 2005) and low forces are achieved by means of small cutting depths during finishing.

Passive damping is achieved by means of applying silicone-based modeling clay on the finished side (side milled under constant force), as depicted in Fig. 6. The damping effect achieved by this technique is demonstrated by the impact response signal at the base of the wall obtained with and without the use of the clay damper (Fig. 6). When an impulse load of 15 N was applied to the structure with external damping, results show that the wall came to rest at less than 3% of the time taken by the undamped structure. The force measured at the base of the wall indicates that the most flexible vibration mode (first mode) has its amplitude reduced to 20% of the undamped case.

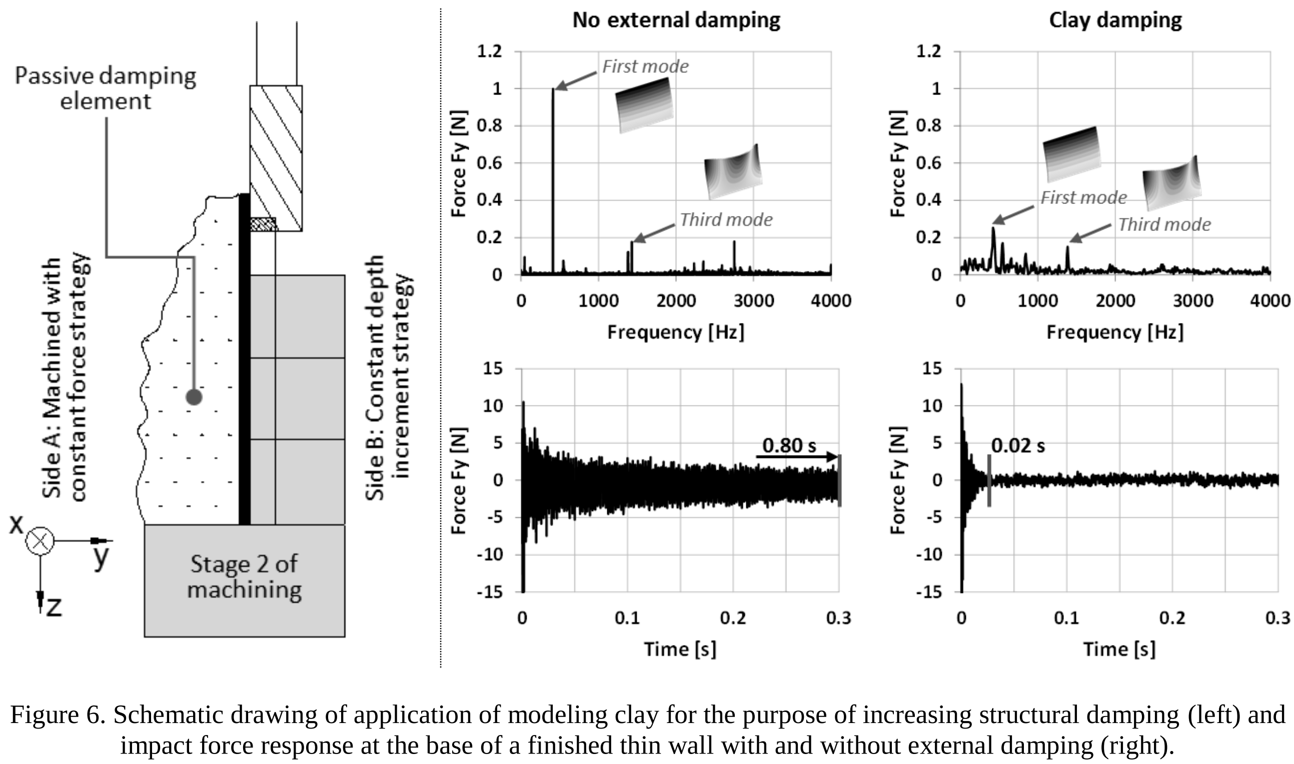


Figure 6. Schematic drawing of application of modeling clay for the purpose of increasing structural damping (left) and impact force response at the base of a finished thin wall with and without external damping (right).

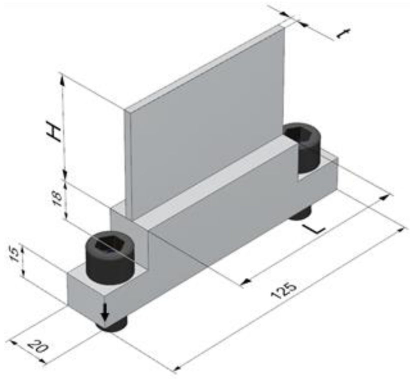
3. EXPERIMENTAL TRIALS

In order to evaluate the effectiveness of the proposed strategy in milling thin-walled features tests were conducted on a cantilever plate part made of aluminum AA 7050 T7451 (Tab. 1). The selection of material and part geometry are due to the wide application of the alloy in aeronautical applications and the higher difficulty associated to machining a plate fixed only by one of its borders. Generally, walls adopted in aerostructures are more rigid than the proposed geometry (Popma, 2010). Since this higher rigidity is usually a manufacturing restriction, the proposed geometry aims at testing a condition that is more severe than those found in typical aerostructures.

Table 1. Workpiece geometry and material characteristics. Source: Federal Aviation Administration (2003).

Workpiece Geometry

H = 48 mm; L = 80 mm; t = 1.1 mm



Material Characteristics: Aluminum AA 7050 T7451	
Chemical Composition (%wt)	Zn 5.7-6.7; Cu 2.0-2.6; Mg 1.9-2.6; Zr 0.08-0.15; Cr <0.04; Fe <0.15; Mn <0.1%; Si <0.12; i<0.06; $Other_{total}$ <0.15; $Other_{each}$ <0.05; Al (rem.)
Mass Density (kg/m^3)	2823
Modulus of Elasticity (GPa)	71.0 (tension) / 73.1 (compression)
Poisson's Ratio	0.33
Brinell Hardness (HB)	140
Tensile Strength at 24° C (MPa)	469
Yield Strength at 24° C (MPa)	400
Shear Modulus (GPa)	26.9
Shear Strength (MPa)	303

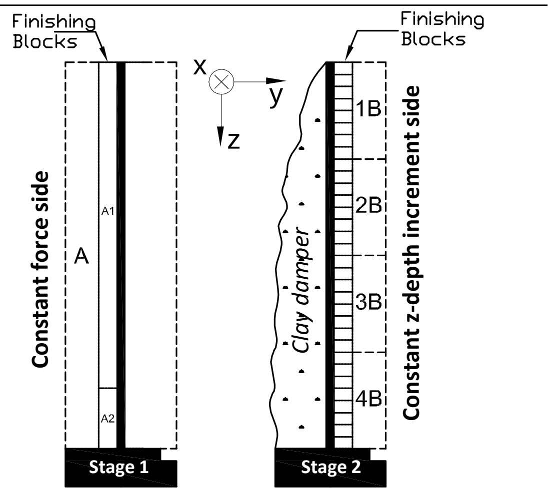
Tests with different cutting tools and parameters were conducted on a CNC machining center (ROMI® D800 AP) in order to evaluate the proposed strategy (Table 2). A first group of tests (condition 1) consisted of using a two-fluted 25° helix angle cutter for the constant force side of the wall, along with a conventional incremental strategy on the second side, as described in Table 2. The second test group (condition 2) consisted of using a three-fluted 45° helix angle cutter for the constant force side and the same strategy as the previous tests for the opposing side, with an increased a_p value.

It should be noted that the first side (constant-force strategy) was entirely finished before the second side (constant z-direction increment) was machined. These two main groups were defined according to commercial availability of cutting tool geometries. Cutting depths for the constant force passes were determined by Eq. (1). On side B of each wall, all conditions were kept the same except for axial cutting depth (a_p). For the second condition of tests cutting depth (a_p) was increased from 1.5 mm to 2.0 mm in order to evaluate the impact on part quality.

For both test conditions, force signals at the base of the workpiece were monitored using a dynamometer (Kistler® 9265B with amplifier 5070A) for stability evaluation. Finished workpieces were later analyzed by means of surface and dimensional measurements. The used equipment consisted of a Mitutoyo® Beyond Crysta C 7106 coordinate measuring machine (CMM) for dimensional and geometrical measurements and a non-contact surface scanner manufactured by Cyber Technologies®, model CT-100.

Table 2. Description of test conditions.

	Parameters	Test Condition 1	Test Condition 2
ROUGHING	a_e [mm]:	8.95	8.95
	a_p [mm]:	12	12
	f_z [mm]:	0.08	0.08
	D [mm]:	25	25
	v_c [m/min]:	400	400
FINISHING	a_e Side A [mm]:	0.5	0.5
	a_e Side B [mm]:	2.0	2.0
	a_p Side A [mm]:	40.4 / 7.6	37.7 / 10.3
	a_p Side B [mm]:	1.5	2.0
	f_z [mm]:	0.07	0.07
	D [mm]:	12	12
	v_c [m/min]:	400	400
	N [RPM]:	10610	10610
	F_{pass} [Hz]:	353	353.7
	Side A Tool:	25°, 2 flutes	45°, 3 flutes
	Side B Tool	25°, 2 flutes	25°, 2 flutes



4. RESULTS AND DISCUSSION

Force signals for test condition 1 indicated that instability took place during cut, possibly due to excessive tool load (Fig 7A). This instability was also observed through chatter marks on the workpiece surface (Fig. 7B). However, for test condition 2, cut was reasonably stable, with lower oscillations around a constant force value for each component, as demonstrated by the filtered signal (low pass – 100 Hz) in Fig. 8B. Additionally, a slight increase in the F_y component of the force signal in Fig. 8 was observed. It is believed that this slight increase is due to larger oscillations of the wall as it becomes more flexible towards the border.

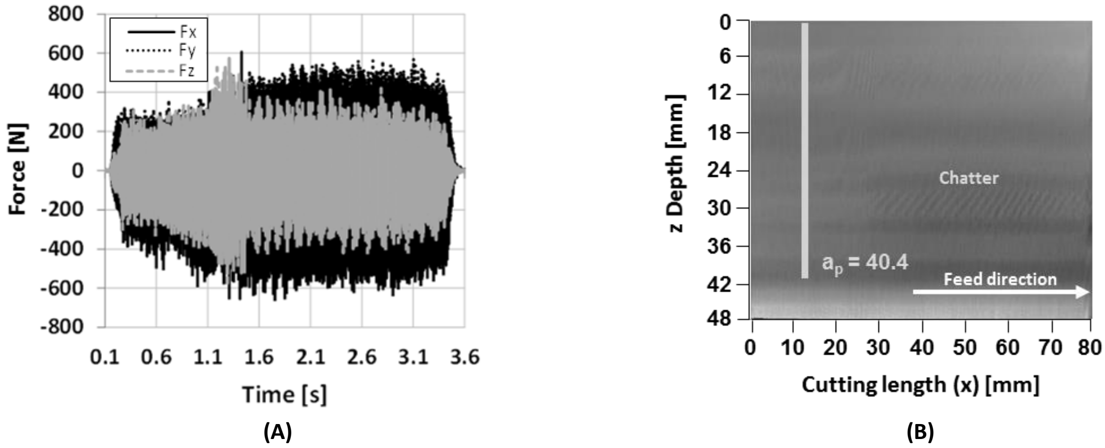


Figure 7. Force results (A) and chatter marks on wall (B) for test condition 1.

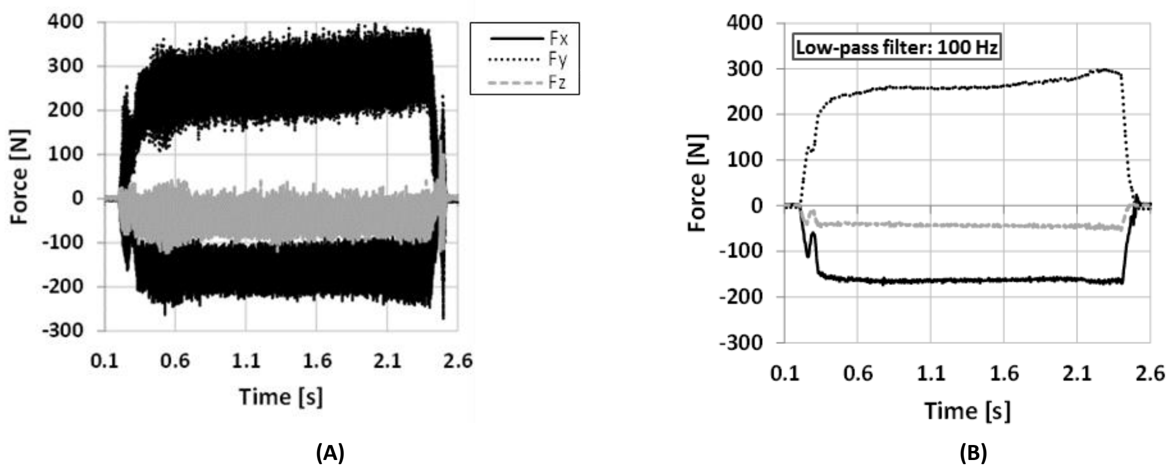


Figure 8. Raw force signal for test condition 2 (A) and corresponding filtered signal (B).

Despite the higher stability of test condition 2, occurrence of re-machining was detected due to tool/workpiece deflection. As a consequence of this, characteristic chips are observed in the second pass of side A (Fig. 9). These chips present a portion of material that is compatible with the current pass and an appendage that was removed from the uncut section left by the previous pass.

Dimensional deviations may be expected as a result of the high deflection during milling. The effect of this indirectly observed deflection on workpiece geometry was investigated by surface (Fig. 10) and dimensional (Fig. 11) measurements. In general, deflections occurred within acceptable limits for the desired application (structural aircraft components) and surface quality is within usual tolerance limits.

Surface scanning results presented in Fig. 10 indicate that even under unstable conditions (condition 1) the achieved roughness (Ra and Rz) is still compliant to usual requirements found in the industry. However, instability should be avoided since it may cause premature tool wear and eventually lead to damaged parts. The higher helix angle tool adopted in condition 2, as compared to condition 1, could be the cause of the more stable results observed. This observation is based on the fact that the peak force components are smaller in the most flexible direction of the wall (y-axis) due to the smoother force profile provided by the larger helix angle. Another possible cause is the higher tooth passing frequency generated by the larger number of flutes ($N_t = 3$), which could have coincided with a higher stability limit region for the tested machining condition.

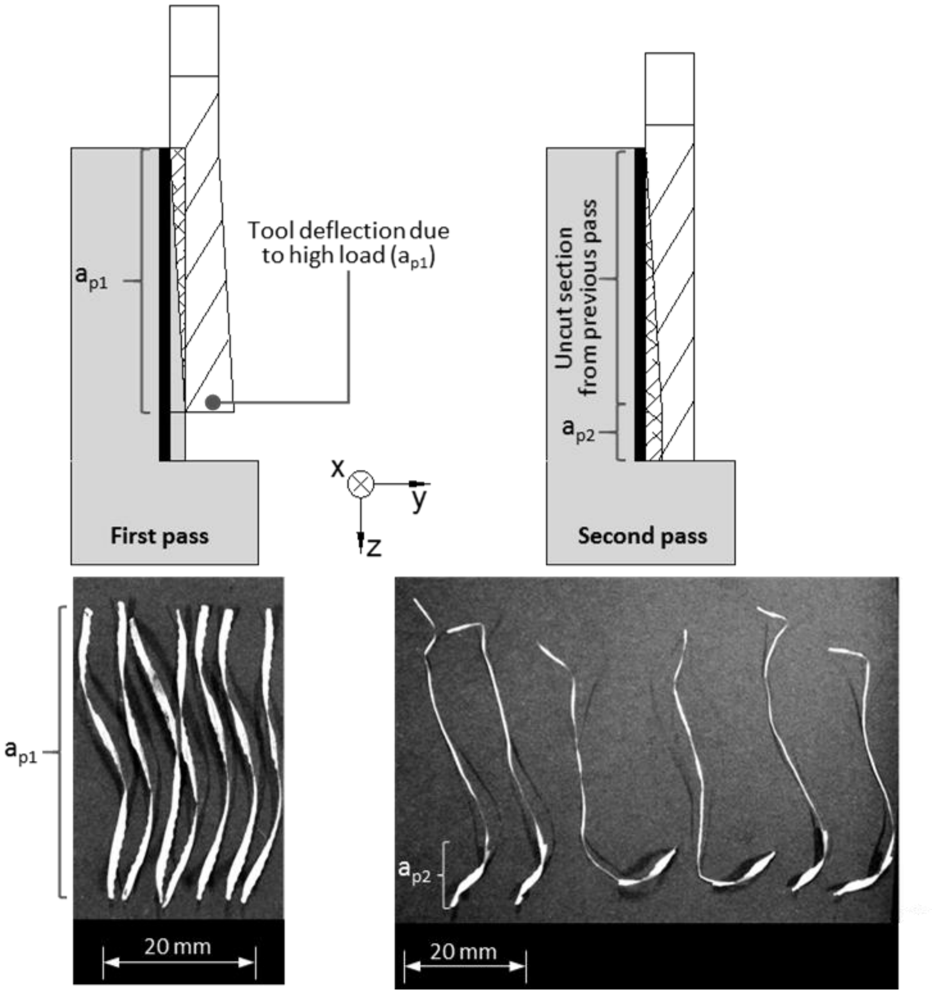


Figure 9. Re-machining phenomenon (above) and typical chips observed in milling (below).

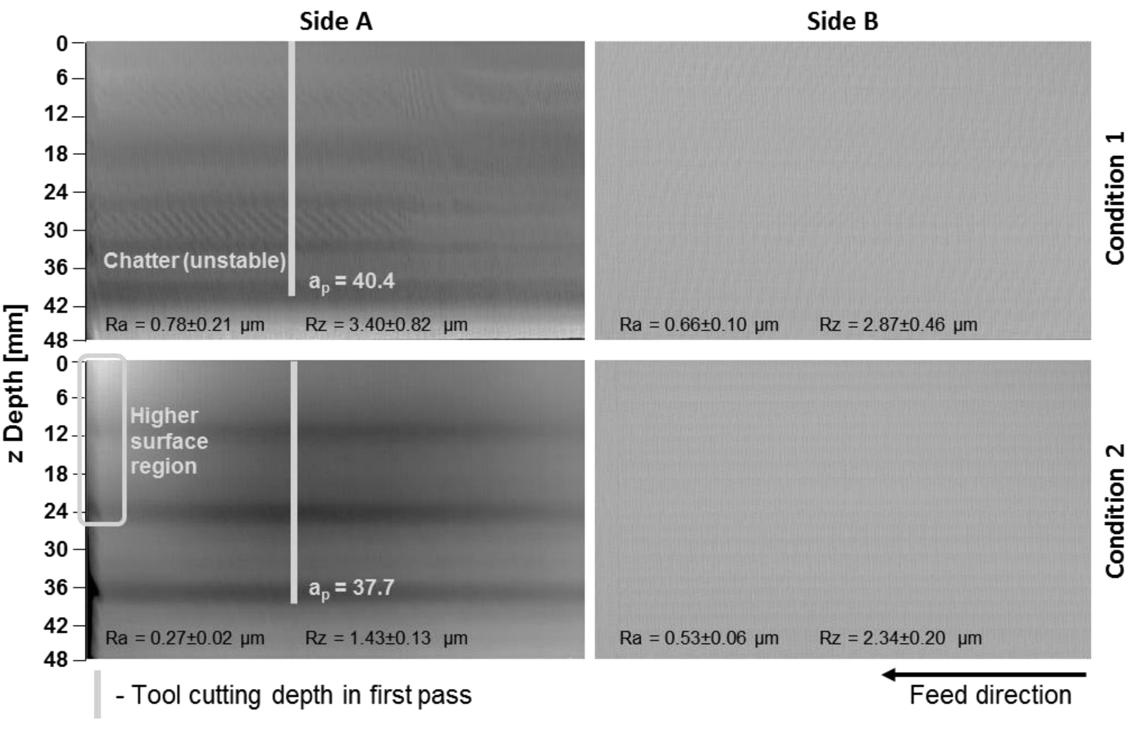


Figure 10. Scanned surfaces of two workpieces (both conditions).

Figure 11 presents a three-dimensional view of measured points on each side of both walls. Through these results it is possible to notice that the second condition generated a slightly thicker wall with higher deflections. The increased thickness is expected since the cutting depth was increased and the workpiece and cutting tools are pushed farther away from each other, consequently undercutting the surface. Also, a slight growth in thickness is observed gradually towards the bottom of the wall. This is believed to happen due to the fact that re-machining does not occur with the same intensity at the bottom, thus less material is removed. As for the increased deflections in condition 2, it is believed that the main cause is related to milling of side A with the constant force strategy. This is explained by the fact that the wall becomes more flexible as the cutting tool reaches the border, thus undercutting the wall at that point. By comparing these results with the surface scanned images, this hypothesis gains support since the surface on side A's border at the top is higher than its middle regions, as indicated in Fig. 10.

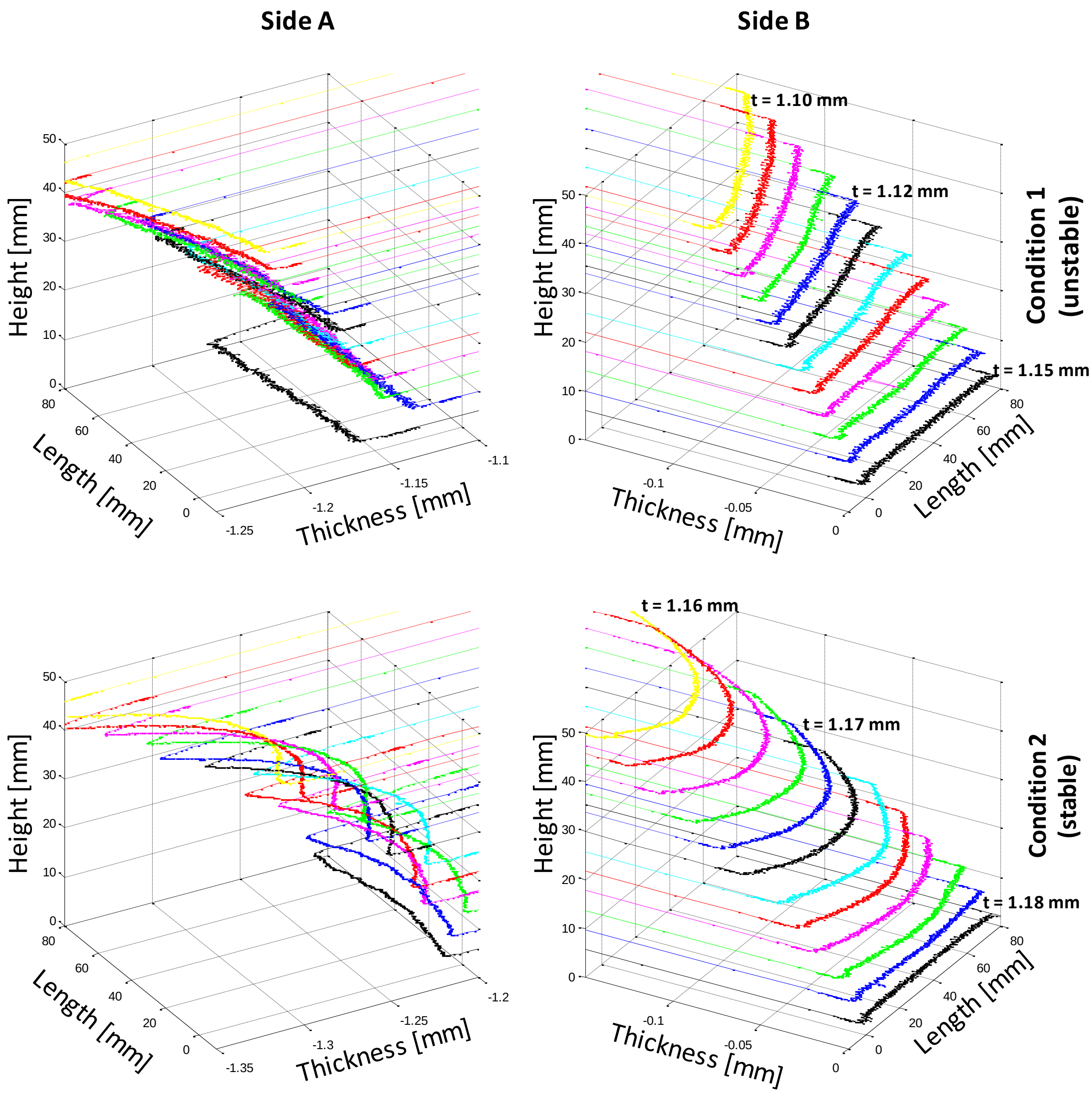


Figure 11. Geometrical measurements for both conditions.

5. CONCLUSIONS

The proposed strategy was able to produce thin walls with adequate quality for applications in manufacturing of structural components. An overall comparison of the produced surfaces reveals that the damping effect when machining side B of both walls provided a stable finishing condition. This strategy is, therefore, adequate when finer finishing is desired with lower processing times, as compared to usual waterline strategies. Another benefit from adopting this strategy is the simple process planning procedure. The proposed method uses a simple algebraic equation to define cutting depth, as compared to prediction approaches, such as stability lobe diagrams, that demand experimental or simulated structural information as well as cutting force data.

However, three drawbacks must be mentioned. First, if dimensional deviations become an issue, they should be dealt with by reducing cutting parameters when machining the first side (side A in this case), or by increasing tool-workpiece stiffness. Second, creating an external damping device adds more complexity to the process, which might make this strategy unfeasible in some cases due to additional processing steps. Finally, the third concern is related to applying this strategy to parts with closed corner geometries. In this specific case, higher tool load occurs at corners and instability is more prone to take place. Therefore, an additional radius relief operation becomes necessary prior to finishing, which in some cases may be a disadvantage.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Altintas, Y.; Budak, E. Analytical Prediction of Stability Lobes in Milling. *CIRP Annals - Manufacturing Technology*, v. 44, n. 1, p. 357–362, 1995.

Bolsunovskiy, S. *et al*. Thin-walled part machining process parameters optimization based on finite-element modeling of workpiece vibrations. *Procedia CIRP*, v. 8, p. 276–280, 2013.

Budak, E. *et al*. Prediction of workpiece dynamics and its effects on chatter stability in milling. *CIRP Annals - Manufacturing Technology*, v. 61, n. 1, p. 339–342, 2012.

Coromant. *Metalcutting Technical Guide*. Sandvik Coromant, 2005. 617 p.

Coromant. *Ferramentas Rotativas: Ferramentas de corte da Sandvik Coromant*. Sandviken: 2010. Tool catalogue for the year 2011.

Federal Aviation Administration. *Metallic Materials Properties Development and Standardization (MMPDS-01)*. s.l. 2003.

Mitsubishi. *General Catalogue*. [s.l.] Mitsubishi Materials, 2013.

Munoa, J. *et al*. Chatter suppression techniques in metal cutting. *CIRP Annals – Manufacturing Technology*, v. 65, n. 2, p. 785–808, 2016a.

Mundim, R.B.; Borille, A.V. An approach for reducing undesired vibrations in milling of low rigidity structures. *The International Journal of Advanced Manufacturing Technology*, v. 88, n. 1–4, p. 971–983, 4 jan. 2017.

Popma, M. *Computer aided process planning for high-speed milling of thin-walled parts*. PhD Thesis. Department of Engineering Technology (CTW) of the University of Twente.Netherlands, 2010. 162 p.

Taegutec. *Ferramentas de Corte para Usinagem.* [S.L.]: Taegutec, 2012. Tool catalogue for the year 2013.

Tlusty, G. *Manufacturing Processes and Equipment*. 1.ed. New Jersey: Prentice Hall, 2000. 928 p.

Schmitz, T. L.; Smith, K. S. *Machining Dynamics: Frequency Response to Improved Productivity*. New York: Springer, 2009. 308 p.

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