# INFLUENCE OF END MILLVARIABLE PITCH ON SURFACE QUALITY OF ALUMINIUM THIN-WALLED PARTS

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In this paper the effect of the end mill variable pitch on the flatness and surface quality of aluminium (EN AW 6082) thin-walled partswas studied. Tests were performed using the HSC 105 linear CNC machine and following cutting parameters: cutting speeds (800, 100, 1200 and 1400 m.min$^{-1}$), feed per tooth (0.12 mm), cutting depth (for roughing 10 mm and for finishing 5 mm). Three teethsolid end millsof 12mm diameter with a regular pitch of120° and an irregular pitch of 125°, 130° and 135° were used. Surface analysis of the processed thin-walled parts showed that both the irregular pitch of the end mills and the used cutting speed have a significant influence on the surfacequality of the thin-walled parts. The best results were obtained in the case of 130°, 135°irregular pitch end mills and cutting speed 800 and1000 m.min$^{-1}$.

**KEYWORDS**

milling, irregular pitchendmills, aluminium thin-walled parts,3D scanning,colour deviation map, flatness

## 1 INTRODUCTION

The thin-walled parts are important in automotive, power and aerospace industries. High-speed cutting (HSC) is the most widened technology for milling of thin-walled parts. A thin-walled part thickness h is lower than height b, (1/80~1/100)b<<h<<(1/8~1/5)b (1) [Aijun 2008]. During milling of thin-walled parts regenerative chatterisgenerated.The chatter is one of the major limitations in milling operations causing poor quality and reduced productivity [Comak 2017].There are several ways, how to eliminate regenerative chatter. The first way is the use of stability lobes to predictthe regenerative chatterin milling [Altitas 1995, Altitas 1999a, Tlusty 1983].The second way is the appropriate machining strategy (material removal way) of the thin-walled parts. An effective machining strategy has a significant impact on the surface quality of the thin-walled parts[Buransky2011, Baranek 2013].The third way is the use of end mills with variable pitch [Altitas 1999b, Suzuki 2016, Yusoff 2016] and variable helix angle [Comak 2017, Yusoff 2016]. The fourth method is the use of the sandwich elements [Sandvik 2017] or the use of the support[Shamoto 2016, Matsubara 2017] and the fixture [Fei 2018]. In this paper the effect of the end mill variable pitch on the flatness and surface quality of aluminium (EN AW 6082) thin-walled parts was studied.

## 2 MATERIALS AND METHODS

### 2.1 *Machine tool, end mills and measuring device*

The experiment was carried outusingHSC 105 linear CNC 5-axis machine. Thetable 1 shows the machining parameters used in the experiment.

**Table 1.** Machining parameters

| Parameters | Value |
|---|---|
| **Cutting speed – $v_c$** | 800, 1000, 1200, 1400 m.min$^{-1}$ |
| **Frequency - n** | 21221, 26526, 31831, 37136 min$^{-1}$ |
| **Feed per tooth - $f_z$** | 0.12 mm |
| **Deep of cut, roughing - $a_p$** | 10 mm |
| **Deep of cut, finishing - $a_p$** | 5 mm |
| **Width of cut, roughing - $a_e$** | 3, 2.5, 1.5 mm |
| **Width of cut, finishing - $a_e$** | 0.5, 0.5 mm |

The three teeth end millsof 12mmdiameter with a regular pitch (120°) and an irregular pitch(125°, 130° and 135°) were used.Thedesign of the end mills was doneusing NumrotoPlus software. The cutting edges of end millswere notprepared. Table 2 shows the parameters of the designed end mills used in the experiment.

**Table 2.** End mills parameters

| Cutter parameter | Value |
|---|---|
| **Diameter - $dm_m$** | 12 h6 mm |
| **Diameter - $D_c$** | 11.95 mm |
| **Diameter- $D_n$** | 11 mm |
| **Length - $l_2$** | 82.5 mm |
| **Length - $l_3$** | 45 mm |
| **Max. depth of cut - $a_{pmax}$** | 20 mm |
| **Pitch and division angle** | 120 – 120 – 120°<br>125 – 117.5 – 117.5°<br>130 – 115 – 115°<br>135 – 112.5 –112.5° |
| **Teeth number - z** | 3 |
| **Helix angle** | 30° |
| **Rake angle** | 10° |
| **Relief angle** | 10° |

Four end mills were tested. Figure 1 shows the designed end mills and the diference between regular and irregular pitch.

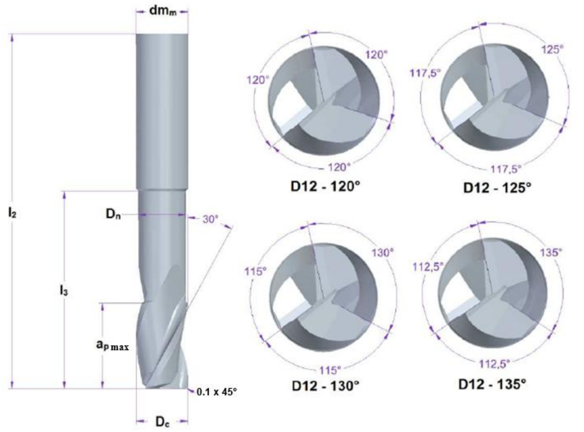


**Figure 1.** The geometrical parameters of end mills

The surface quality and flatness were measured by GOM Atos II TripleScanoptical 3D scanner.The measuring volume MV 170 (170 x 130 x 130) was used for scanning the aluminium thin-walled parts. The chalk spray was appliedtoeliminate shiny surface.For the alignment of 3D scan to CAD model the geometrical elements was chosen (Fig. 2), concretely three planes (yellow, red and blue).

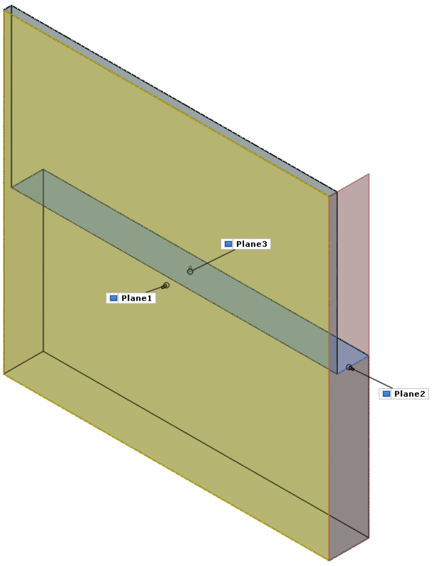


**Figure 2.** Alignment by geometrical elements (3 planes))

Surface quality was evaluated bythe colour deviation maps. Figure 3 shows themethod of evaluation of the surface quality, which is based onsurface comparison (CAD model vs. 3D Scan). That method was completely described in thefollowing paper[Baranek 2013].

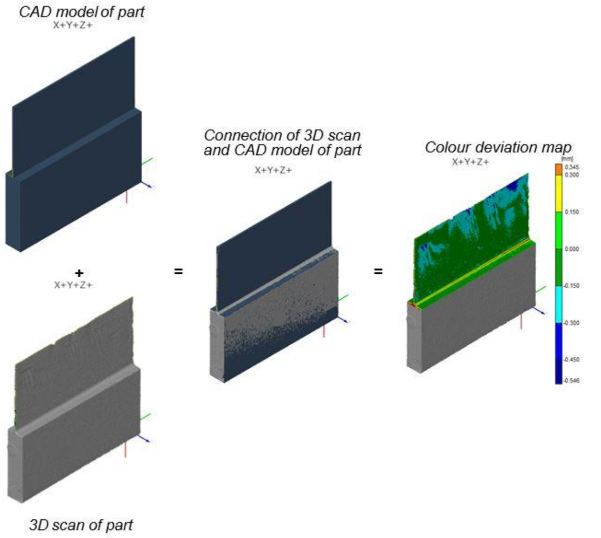


**Figure 3.** Scheme of colour deviation map development (Baranek 2013)

## 2.2 *Workpiece and strategy of milling*

The workpiece material was aluminium alloy (EN AW 6082).The size of the blank was 80 x 80 x 10 mm. Figure 4 shows clamping of the blank in the machining vice. The overhang of the blank was 56 mm.

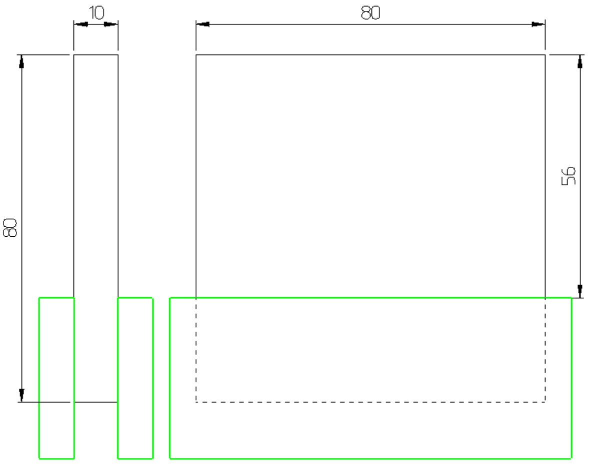


**Figure 4.** Drawing of the blank (black colour) and the clamping jaws (green colour)

For the definition of thin-walled partthe following formula is used (1) to prove that the part is thin-walled.

$$(1/80 \sim 1/100) \times b < h < (1/8 \sim 1/5) \times b \qquad (1)$$
$$(1/100) \times 40 < h < (1/5) \times 40$$
$$0.4 < h < 8$$

Table 3 and table 4 show the chemical composition and physical-mechanicalproperties of EN AW 6082 alloy, respectively. It is known that themachinability of the material is good.

**Table 3.** Chemical composition of EN AW 6082

| Chemical Element | % Present |
|---|---|
| **Manganese (Mn)** | 0.40 - 1.00 |
| **Iron (Fe)** | 0.0 - 0.50 |
| **Magnesium (Mg)** | 0.60 - 1.20 |
| **Silicon (Si)** | 0.70 - 1.30 |
| **Copper (Cu)** | 0.0 - 0.10 |
| **Zinc (Zn)** | 0.0 - 0.20 |
| **Titanium (Ti)** | 0.0 - 0.10 |
| **Chromium (Cr)** | 0.0 - 0.25 |
| **Other (Each)** | 0.0 - 0.05 |
| **Other (Total)** | 0.0 - 0.15 |
| **Aluminium** | Balance |

**Table 4.** Physical and mechanical properties of AW 6082

| Property | Value |
|---|---|
| **Density** | 2.70 g/cm³ |
| **Melting Point** | 555 °C |
| **Thermal Expansion** | 24 x10^-6 /K |
| **Modulus of Elasticity** | 70 GPa |
| **Thermal Conductivity** | 180 W/m. K |
| **Electrical Resistivity** | 0.038 x10^-6 Ω .m |
| **Density** | 2.70 g/cm³ |
| **Melting Point** | 555 °C |
| **Thermal Expansion** | 24 x10^-6 /K |
| **Proof Stress** | 255 Min MPa |
| **Tensile Strength** | 300 Min MPa |
| **Elongation A50 mm** | 9 Min % |
| **Hardness Brinell** | 91 HB |

The progressive radial depth of cut (RDOC) strategy was used (Figure5). The method of material removalaccording to RDOCisusually used formilling of parts with medium height and thickness ratio <30:1. For the studied samples, the ratio was 20:1. Toolpaths and NC programs were generated using Autodesk PowerMILL software.

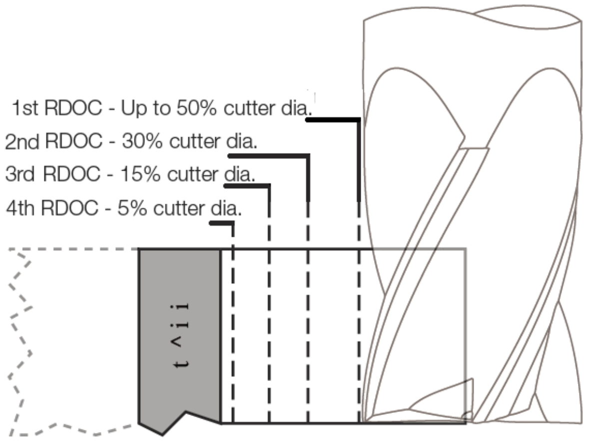


**Figure 5.** RDOC milling strategy (Helical2018)

The thin-walled parts were milled only from one side. Figure 6 shows the final shape of the thin-walled part after milling.

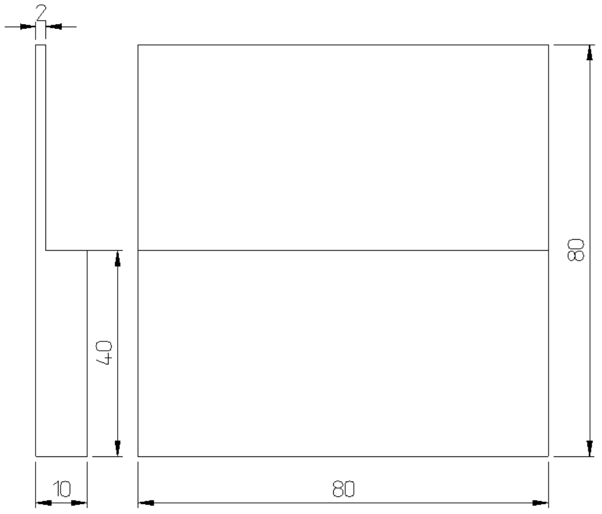


**Figure 6.** Shape and dimensions of thin-walled parts after milling

## 3 RESULTS AND DISCUSSION

The surface deviations were the largest in the case of theregular pitch end mill for all the cutting speeds, as shown in Figs. 7, 8, 9, and 10.The toolmarks after milling are visible at the processed surface, which can be attributed to vibrations.

In the case of125° irregular pitch end mill and cutting speed 1200 m.min$^{-1}$, the deviation between the CAD modeland the 3D scan was lesscompared with that of 120°regular pitch end mill.Nevertheless, the toolmarksafter milling were also visible in this case due to the chatter of the thin-walled parts.

The smallest deviations from the CAD model were obtained in milling using 130° irregular pitch end mill and cutting speed 1000 m.min$^{-1}$ (Figure 16).The toolmarksat the surface of the workpiece were the smallest in this case.

The deviation from the CAD modelwith respect to 135°irregular pitch end mill and cutting speed 800 m.min$^{-1}$was almost identical compared with 130° irregular pitch end mill and the cutting speed1000 m.min$^{-1}$. The toolmarks on the workpieces were very similar.

It can be thus concluded thatthe comparable surface quality can be achievedusingboth 135° irregular pitch end millandcutting speed800 m.min$^{-1}$,as well as130° irregular pitch end mill andcutting speed1000 m.min$^{-1}$.

From the surface quality point of view the decisive measured factor is flatness.When using the 120° regular pitch and the 125° irregular pitch end mills, the flatness was more than 0.1 mm, whereasfor the 130° and 135° irregular pitch end mills, the flatness was less than 0.11 mm.

As can be seen in Fig. 7-22, the irregular pitch of end mill causes different feed per tooth which contributes to eliminate regenerative chatter and decreases the size and formation of the tool marks during machining.

Although the use of end mills with 130° and 135°irregular pitch causes smaller flatness deviation of the thin-walled parts, the higher dimension deviations can be seen in color deviation maps for certain cutting speeds, which indicates that the used cutting conditions were not verified by stability lobes and the thin wall is probably deflected towards cutting tool when milling. In such cases, whenthethin wall was machined to inaccurate dimension, it is necessary to adjust the cutting conditions according to stability lobes, adjust machining allowances or use such cutting speeds which cause minimal dimension deviation.

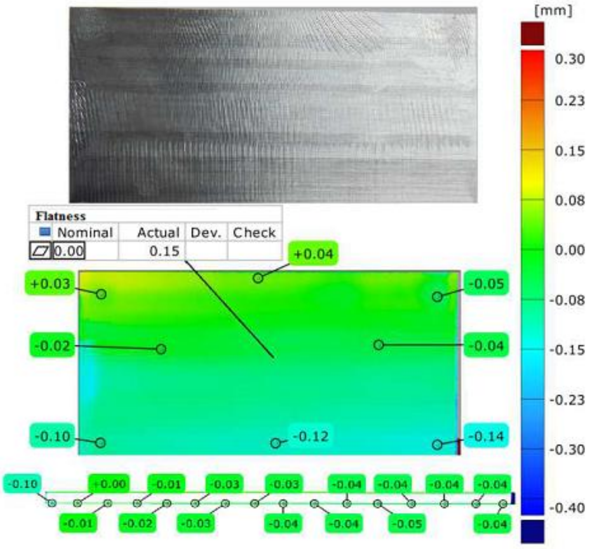


**Figure 7.** Color deviation map for D12-120°, $v_c$ = 800 m.min$^{-1}$

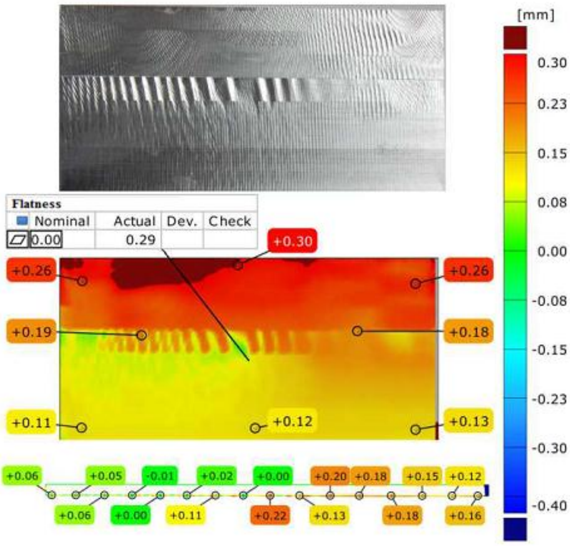


**Figure 8.** Color deviation map for D12-120°, $v_c$ = 1000 m.min$^{-1}$

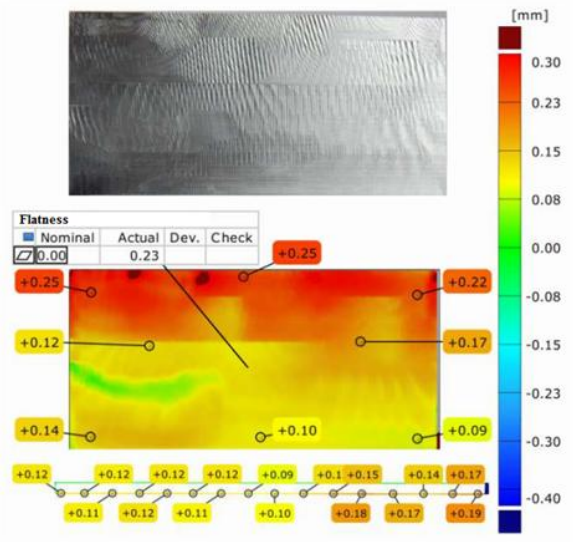


Figure 9. Color deviation map for D12-120°, $v_c$ = 1200 m.min$^{-1}$

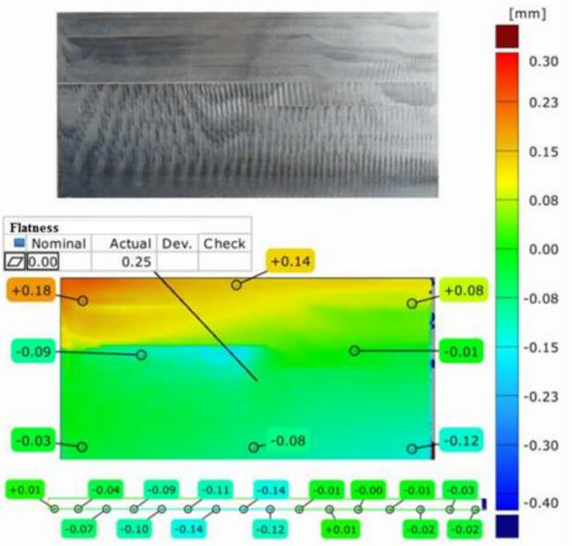


Figure 12. Color deviation map for D12-125°, $v_c$= 1000 m.min$^{-1}$

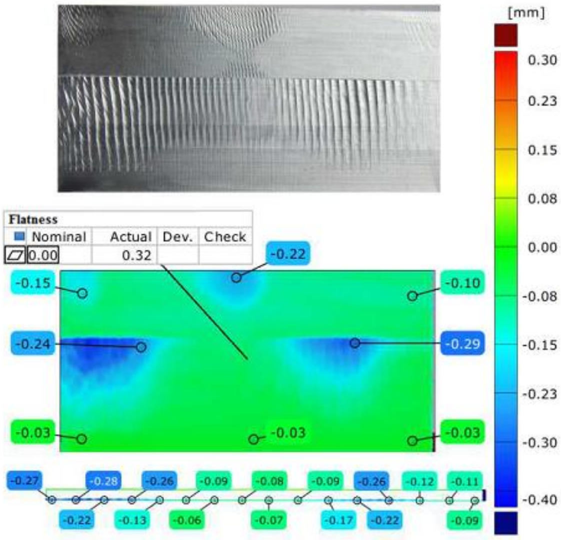


Figure 10. Color deviation map for D12-120°, $v_c$ = 1400 m.min$^{-1}$

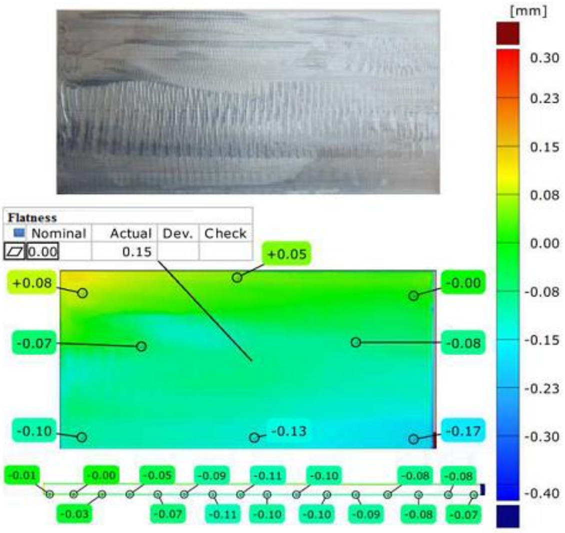


Figure 13. Color deviation map for D12-125°, $v_c$ = 1200 m.min$^{-1}$

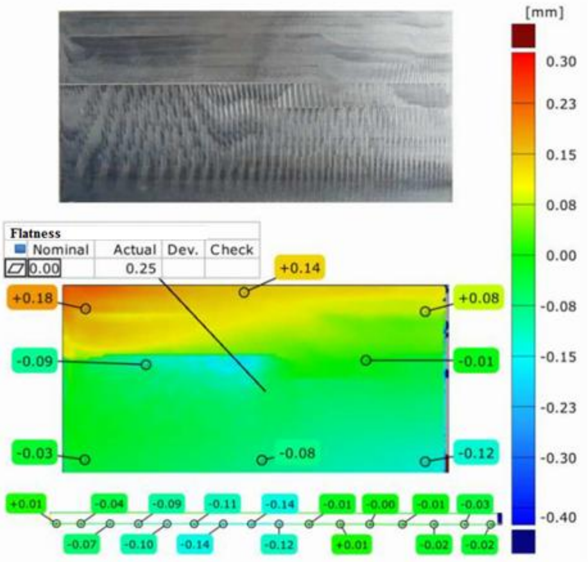


Figure 11. Color deviation map for D12-125°, $v_c$ = 800 m.min$^{-1}$

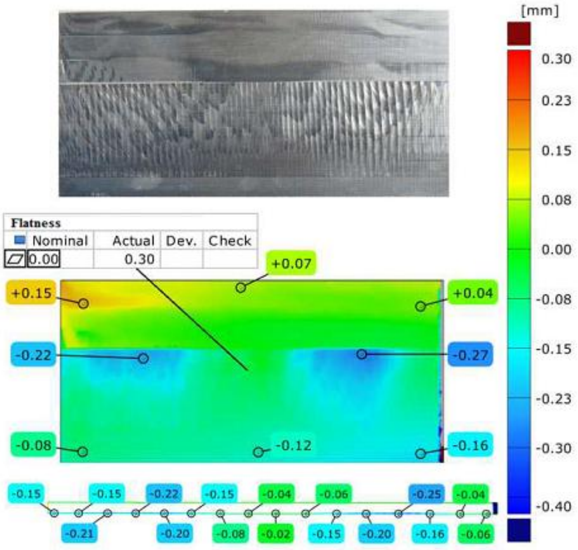
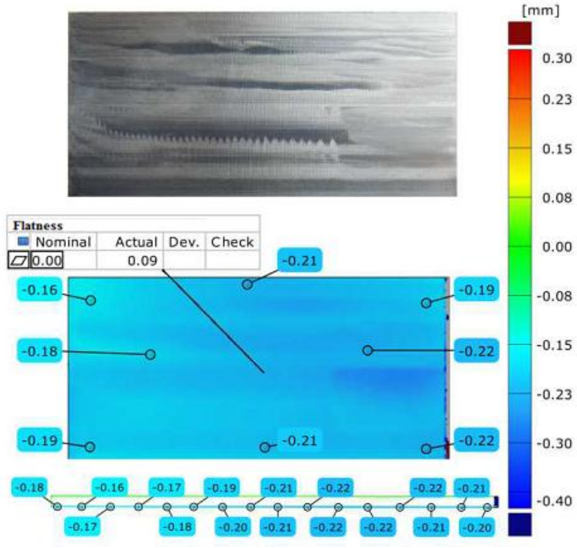
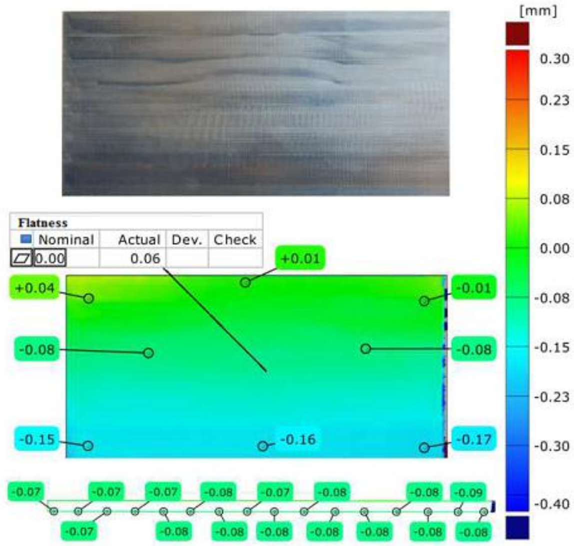


Figure 14. Color deviation map for D12-125°, $v_c$ = 1400 m.min$^{-1}$



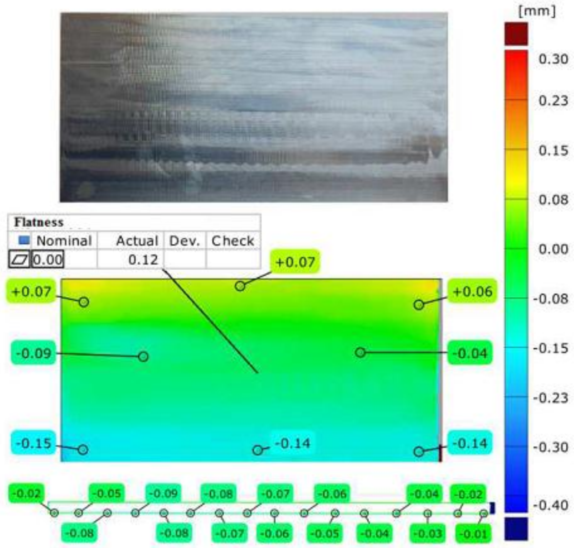
| Flatness | | | |
|---|---|---|---|
| Nominal | Actual | Dev. | Check |
| 0.00 | 0.09 | | |

**Figure 15**. Color deviation map for D12-130°, $v_c$ = 800 m.min$^{-1}$



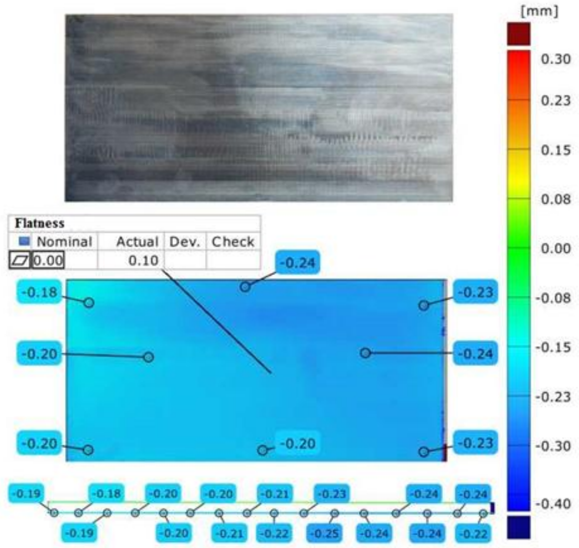
| Flatness | | | |
|---|---|---|---|
| Nominal | Actual | Dev. | Check |
| 0.00 | 0.06 | | |

**Figure 16**. Color deviation map for D12-130°, $v_c$ = 1000 m.min$^{-1}$



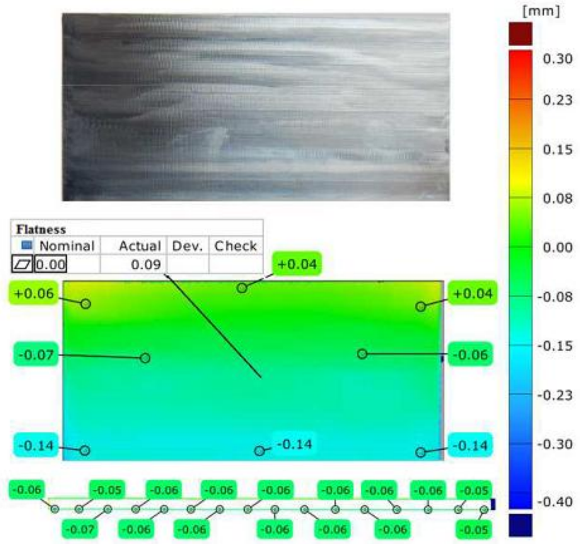
| Flatness | | | |
|---|---|---|---|
| Nominal | Actual | Dev. | Check |
| 0.00 | 0.12 | | |

**Figure 17**. Color deviation map for D12-130°, $v_c$ = 1200 m.min$^{-1}$



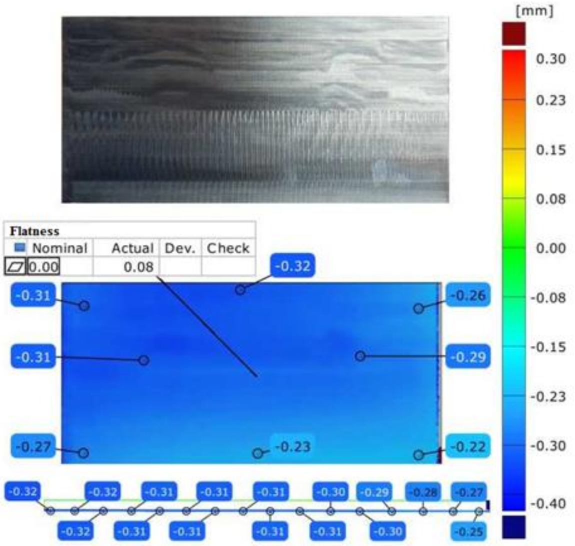
| Flatness | | | |
|---|---|---|---|
| Nominal | Actual | Dev. | Check |
| 0.00 | 0.10 | | |

**Figure 18**. Color deviation map for D12-130°, $v_c$ = 1400 m.min$^{-1}$



| Flatness | | | |
|---|---|---|---|
| Nominal | Actual | Dev. | Check |
| 0.00 | 0.09 | | |

**Figure 19**. Color deviation map for D12-135°, $v_c$ = 800 m.min$^{-1}$



| Flatness | | | |
|---|---|---|---|
| Nominal | Actual | Dev. | Check |
| 0.00 | 0.08 | | |

**Figure 20.** Color deviation map for D12-135°, $v_c$ = 1000 m.min$^{-1}$

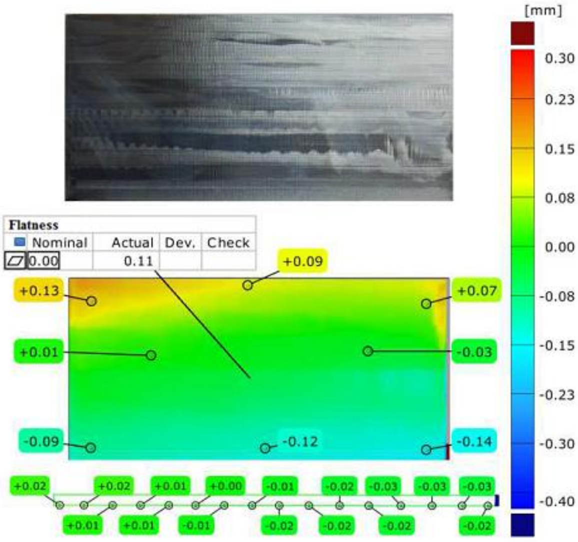


**Figure 21**. Color deviation map for D12-135°, $v_c$ = 1200 m.min$^{-1}$

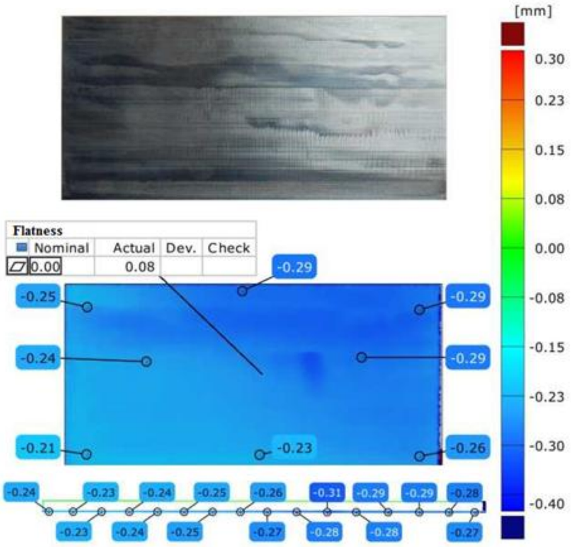


**Figure 22**: Color deviation map for D12-135°, $v_c$ = 1400 m.min$^{-1}$

## 4 CONCLUSIONS

Various methods are used in order to eliminate self-excited vibrations (chatter). The present paper describes the influence of variable pitch of the end mills on surface quality and flatness of the processed aluminium thin-walled parts.It was shown that varying variable pitch of end mill has significant influence on surface quality.Use of the irregular pitch end millslead to a decrease in the chatterduring milling process of the thin-walled parts. The experiment proved that the use of lower cutting speeds during the machining led to the surface quality improvement of the thin-walled parts. However, for irregular pitch end mills the higher cutting speed can be used without producing the significant deformation of thin-walled part.Further research will be focused on the influence of helix angleon the surface quality of the thin-walled parts.

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