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Influence of pre-machining on post-machining deformation of thin-walled elements made of aluminium alloy EN AW-2024

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Abstract. The paper presents analysis of influence of pre-machining, consisting of removing the textured surface layer of the semi-finished product formed after plastic working, on deformation of thin-walled elements made of EN AW-2024 alloy after milling. The textured layer was removed from surface opposite to the machined surface. During tests, the influence on thin-walled elements deformation of the following machining strategies was analysed: High Speed Cutting (HSC), High Performance Cutting (HPC), and hybrid strategies HPC + HSC, HPC + CM, and HPC + CM (CM – Conventional Machining). On the basis of received results it was determined that residual stresses stored in subsurface, rolled, and unmachined surface layer have significant influence on value and character of deformations of thin-walled elements. Removing the textured surface layer formed after rolling changes character and value of the deformations of thin-walled elements. The largest difference between samples with initially removed textured layer and samples without such machining was determined for HPC + CM milling strategy. For this strategy, deformations without pre-machining were much larger than in the case of samples with removed textured surface layer.

1. Introduction

Thin-walled integral elements, characterising mainly with small mass in comparison to overall dimensions and unitary structure, currently replaced elements that were made and combined from even several hundred parts. For example, main landing gear flap of one of transport airplanes, which used to be produced as a unit combined of parts made of profiles and plates, due to using numerically controlled machining centres and high-efficiency technologies such as HPC and HSC, currently is the only structural element [1], [7], [18].

The tendency to simplify semi-finished products (production from monoblocks) and decrease materials usage degree becomes more and more frequent. Copious amount of chips created during machining process, reaching in certain cases over 90% of semi-finished product mass, is currently economically justified. These industrial practises find variety of uses in aeronautics. However, using modern, high-efficiency technologies of High Speed Machining probably influences process of generating higher residual stresses, resulting in occurrence of post-machining deformations. The necessity of decreasing mass of structural elements bring about decrease of their rigidity during machining. When walls thickness is lower than a few millimetres, thin-walled element undergoes deformation after unfastening from the machine grip [3], [5], [7], [11], [15], [16], [18].

Plane parts are frequently made of rolled plate from aluminium alloys, which accumulate residual stresses resulting from semi-finished product technological history (in this case, the rolling process).
During removing of material surface layer, balance of resided stresses is destroyed that as consequence leads to undesired deformations. Thus, it is assumed that post-machining deformation of thin-walled elements result from residual stresses, generated during both machining and semi-finished product production. Deformation values of thin-walled elements are very difficult to predict. It results from the wide range of factors that have impact on them [5], [7-10], [13], [14], [17], [19]. Authors of papers [7], [17] point out that besides residual stresses, they depend also on temperature, as well as force of gripping and cutting.

The literature [5], [7], [15], [20], [21] offers several ways to minimize thin-walled elements deformation, e.g.:
- technological parameters optimization,
- tool geometry optimization,
- tool path optimization,
- proper machine grip selection,
- simultaneous workpiece wall milling from both sides.

Additionally, machining allowance of 0.1 ÷ 0.2 mm is recommended.

Recently, milling has developed as method of very wide variety of uses, enabling to produce very complex elements. High-efficiency technologies such as High Speed Cutting and High Performance Cutting are developing very dynamically. In the most general way, HSC is characterised as machining of high cutting speed and small cross-sections of the machined layer, while HPC utilises average cutting speed but significantly higher technological parameters such as: depth of cut and feed per tooth [2], [4], [6], [12].

The research conducted on post-machining deformations of thin-walled elements made of aluminium alloy EN AW-2024 allowed to conclude, that removing textured surface layer formed after plastic working might significantly influence the character and value of the occurring deformations.

2. Methodology

The aim of the research was to determine the influence of pre-machining on post-machining deformations of thin-walled elements made of aluminium alloy EN AW-2024. Figure 1 presents experiment outline. The object of the study was a flat sample of dimensions 10x45x210 mm. Independent variables included machining strategies of a different range of technological parameters (ap, vc, fz) and pre-machining consisting of removing textured surface layer formed after plastic working. The dependent variable was received post-machining deformations. Fixed factors included the machined material (aluminium alloy EN-AW 2024) and work environment, while interference factors consisted of MGWT (machine-grip-workpiece-tool) system instability and samples inaccuracy.

![Figure 1. Experiment outline.](image)

Within the experiment, five machining strategies were examined, i.e.:
- High Performance Cutting (HPC),
- High Performance Cutting and Conventional Machining (HPC + CM),
- High Performance Cutting and High Speed Cutting (HPC + HSC),
High Speed Cutting (HSC),
- High Speed Cutting and Conventional Machining (HSC + CM).

Additionally, two variants of the samples were analysed:
- without pre-machining (without removing textured surface layer formed after rolling),
- with pre-machining (with removing textured surface layer formed after rolling).

The textured layer was removed from the surface opposite to the machined layer. During this processing, technological parameters of conventional machining were used, i.e.: \( a_p = 0.4 \) mm, \( v_c = 200 \) m/min. Table 1 presents technological parameters values of specific milling strategies.

| Technological parameters | HPC | HPC + CM | HPC + HSC | HSC | HSC + CM |
|--------------------------|-----|---------|-----------|-----|---------|
| Depth of cut \( a_{p1} \) [mm]² | 4.5 | 4.3 | 0.4 | 4.3 | 0.4 | 0.95; 0.45¹ | 0.95 | 0.45 |
| Depth of cut \( a_{p2} \) [mm]³ | 4.3 | 4.1 | 0.4 | 4.1 | 0.4 | 0.9; 0.5¹ | 0.9 | 0.5 |
| Milling width \( a_e \) [mm] | 18.75 | 18.75 | 12 | 18.75 | 12 | 12 | 12 | 12 |
| Cutting speed \( v_c \) [m/min] | 1 000 | 1 000 | 200 | 1 000 | 1 200 | 1 200 | 1 200 | 200 |
| Feed per tooth \( f_z \) [mm/tooth] | 0.1 | 0.1 | 0.02 | 0.1 | 0.02 | 0.02 | 0.02 | 0.02 |
| Rotational speed \( n \) [rpm] | 12 | 12 | 3 979 | 12 | 23 | 23 | 873 | 3 979 |
| Feed rate \( v_f \) [mm/min] | 3 820 | 3 820 | 239 | 3 820 | 1 432 | 1 432 | 1 432 | 239 |
| No. of passes \( i \) [-] | 2 | 2 | 1 | 2 | 1 | 9; 1* | 9 | 1 |

¹ Final pass
² Depth of cut \( a_{p1} \) for samples without removing textured surface layer formed after plastic working
³ Depth of cut \( a_{p2} \) for samples with removing textured surface layer formed after plastic working

The machined material was aeronautical EN AW-2024 aluminium alloy, chemical composition of which presents Table 2. The milling was conducted on Avia VMC 800HS vertical machining centre.

Table 2. EN AW-2024 alloy chemical composition.

| EN AW-2024 | Si | Fe | Mg | Cu | Mn | Zn | Cr | Zr | V | Ti | Other |
|-------------|----|----|----|----|----|----|----|----|----|----|-------|
|             | 0.07 | 0.20 | 1.3 | 4.6 | 0.56 | 0.11 | 0.01 | 0.01 | 0.01 | 0.02 | 0.05 |
| Alloy limits [%] | min | max |
| Si | 0.00 | 0.00 | 0.00 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 |
| Fe | 0.50 | 0.50 | 1.80 | 4.90 | 0.90 | 0.25 | 0.10 | 0.05 | 0.05 | 0.15 | 0.15 |

During machining, two milling cutters were used:
- Kennametal indexable end milling cutter (symbol: 25A03R044B25SED14) with carbide inserts (symbol: EDCT140416PDFRLDJ) used in HPC strategy,
- Sandvik monolithic carbide milling cutter (symbol: R216.33-16040-AC32U H10F) used in Conventional Machining and HSC technology.

Sylvac CL44 digital sensor of measuring resolution equal 0.001 mm was used for measuring post-machining deformations. Measurements were conducted after unfastening samples from the machine grip. Additionally, for High Performance Cutting strategy and two types of samples (with and without removing textured surface layer formed after plastic working), verification measurements were taken using optical scanner ATOS Capsule of GOM.

Figure 2 presents a post-machining sample with marked overall dimensions of 10x45x210 mm, length of cut out area equal 160 mm, and target bottom thickness amounting to 1 mm. Additionally, the measuring plane in which the post-machining deformation was measured with Sylvac sensor was marked.
Samples were cut out of the rolled plate with thickness of 10 mm. During machining, feed direction was parallel to the rolling direction.

3. Results
In the first stage of the research, the results of samples in which the textured surface layer formed after plastic working was not removed were analysed. Figure 3 presents values of samples deflection $f$ after their machining, measured along measuring section $l$ for the five researched strategies. On the basis of received results it was determined that for all researched strategies, the deflection has a negative value (that is, position of deviation below the “zero” line). For specific strategies, the following maximum deflection values were obtained: $f_{\text{max}} = -0.241$ mm (HPC), $f_{\text{max}} = -0.156$ mm (HPC + CM), $f_{\text{max}} = -0.128$ mm (HPC + HSC), $f_{\text{max}} = -0.045$ mm (HSC), and $f_{\text{max}} = -0.040$ mm (HSC + CM). The largest deflection was determined for HPC strategy and the smallest for the combination of HSC and Conventional Machining (CM).

In the next stage, the samples in which the textured surface layer formed after plastic working was removed were analysed. Figure 4 presents values of deflection $f$ of samples after machining, measured along measuring section $l$, for the five examined strategies. In this case, as well, the deflection has negative values. For the samples with removed textured surface layer, after machining with the specific methods, the following maximum deflection values were achieved: $f_{\text{max}} = -0.196$ mm (HPC), $f_{\text{max}} = -0.030$ mm (HPC + CM), $f_{\text{max}} = -0.156$ mm (HPC + HSC), $f_{\text{max}} = -0.105$ mm (HSC), and $f_{\text{max}} = -0.069$ mm (HSC + CM). The largest deflection was received for HPC strategy, while the smallest one was received for the combination of HPC and Conventional Machining (CM).
Figure 4. Deflection $f$ along measuring section $l$ of samples with removing the textured surface layer formed after plastic working.

In order to compare results received from samples with and without removing the textured surface layer, maximum deflection values for the specific machining strategies are presented in Figure 5.

Figure 5. Comparison of maximum deflection $f_{\text{max}}$.

The presented comparison allowed to determine that the largest post-machining deflection $f_{\text{max}}$ was received after machining with HPC strategy regardless of presence or absence of the pre-machining. For the HPC + CM combination, after removing the textured layer the deflection value was over five times lower than in the samples without pre-machining. For strategies HPC + HSM, HSC, and HSC + CM, larger deflection was received for samples that underwent pre-machining.

Figures 6 and 7 present results of deformation measurements conducted with optical scanner ATOS of GOM for High Performance Cutting strategy and two types of examined samples.

After comparing results received in measurements conducted with digital sensor and optical scanner, it was determined that they are congenial and in the both cases deformation assumes shape of deflection of negative character.
Figure 6. Deformation measurement conducted with optical scanner ATOS GOM: HPC strategy (sample without removing the textured surface layer formed after plastic working).

Figure 7. Deformation measurement conducted with optical scanner ATOS GOM: HPC strategy (sample with removing the textured surface layer formed after plastic working).

4. Conclusion
On the basis of received results, the following conclusions were formulated:
1) For samples without removing of textured surface layer formed after plastic working, the largest post-machining deflection was received for the HPC strategy, and the smallest for the combination of HSC and Conventional Machining (CM).
2) In the case of samples with removed textured surface layer formed after rolling, the largest deflection was received for the HPC strategy, and the smallest for the combination of HPC and Conventional Machining (CM).

3) Selection of a right machining strategy presents opportunity to shape character and value of occurring post-machining deformation of thin-walled elements.

4) Precise estimation of thin-walled elements deformation is extremely hindered due to significant number of factors influencing its value as well as stochastic character of rolling and machining processes.

5) Utilising pre-machining consisting of removing textured surface layer formed after rolling influences post-machining deformations of thin-walled elements made of aluminium alloy EN AW-2024.

6) For strategies using HPC technology (HPC, HPC + CM) and pre-machining, the deformation decreased in comparison to the samples without pre-machining, while for the remaining strategies (HPC + HSC, HSC, HSC + CM), the deformation increased.

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