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Original Research

Implementation of Technology for High-Performance Milling of Aluminum Alloys Using Innovative Tools and Tooling

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Abstract

The research described in the concerns the development and implementation of new clamping technologies used in machining, particularly for thin-walled structural components of aircraft and helicopters. Among other things, the performance of the Schunk Vero-S Aviation clamping system in machining landing gear beams from 7075 T6 aluminum alloy was analyzed, resulting in significant increases in production efficiency and improvements in the geometric quality of machined parts. During experimental research and implementation testing, special chucks were used on the Schunk Vero-S Aviation system for machining the chassis beam. The results showed an improvement in the quality and accuracy of machined parts compared to traditional clamping methods. Increased production efficiency by minimizing scrap and significantly better surface quality and geometric properties compared to conventional clamping. These studies were conducted as part of a project by Ultratech Sp. z o.o. which was implementing a project co-financed by European Funds "Development and implementation of an innovative clamping method for milling processing of thin-walled structural elements of helicopters and airplanes".

Keywords: non-rigid parts, thin-walled element, titanium and aluminium alloys, high-performance milling

1. Introduction

Proper semi-finished product selection for aircraft structural elements significantly affects the further technological process, including the efficiency. It is characteristic that in the field of lightweight alloys processing there is a tendency to simplify the design of semi-finished geometry products to reduce material usage. It is also common for technological processes to produce a product which weight of the finished element does not exceed 5% of weight of a semi-finished product (Cichosz, 2022). To reduce the cost of total part production, the time needed to prepare the semi-finished product is minimized due to of increase of the machining process performance from solid material (Oczoś & Kawalec, 2012).

Machine tools, cutting tools, process parameters and the type of fixtures objects play a significant role in this process (Zawada-Michałowska & Kuczmaszewski, 2020). Clamping technology in high-performance machining plays a very important role in the comprehensive optimization of process chains. It determines the times of auxiliary processes, enables the implementation of these processes and influences the quality of the workpiece. The current research evaluates three different reference strategies in horizontal process chains and discusses the impact of fixture dynamics on workpieces. To achieve optimal performance in the parts supply chain, optimizing solutions for securing products during milling is crucial (Aurrekoetxea et al., 2022).

Important in the case of machining high-silicon silumins is to consider wear of applied cutting tools. The durability of tools, especially in automated machining on numerically controlled machine tools, mostly concerns elements used in the automotive industry (Pieśko & Kuczmaszewski, 2022). When machining high-silicon silumin alloys, tools with blades made of super-hard materials are used in this case - polycrystalline diamond due to its resistance to abrasive wear. For machining applications of 7075 aluminum alloys, in most cases fine-grained sintered carbide tools with appropriate coatings or polished flutes and appropriate cutting-edge microgeometry are used. The use of tools with PCD inserts for machining low-silicon aluminum alloys used in aerospace applications is intended to increase the efficiency of the cutting process by increasing the cutting speed and feed and improving the surface quality after machining (Ostrowski et al., 2013). The study presents a strategy for processing thin-walled elements.

The cutting process causes many technique problems, such as surface deformations and stresses, leading to increased production costs and extended production time. Various anti-vibration methods were used to avoid deterioration of the geometric quality of the surface and surface roughness. To minimize shape deviations and surface roughness, the machining strategy, cutting speed, cutting parameters, including feed per tooth and cutting depth, were optimized. These actions are aimed at reducing the cutting force perpendicular component to the machined surface, which is crucial for the quality of the final product (Bałon et al., 2017).

Many studies have been published on the selection of appropriate cutting parameters to avoid vibrations and a key aspect of high-performance machining is the transfer of this process into a digital space - Virtual MACHINING. Optimization and selection of parameters to create a digital twin of the process is a way cheaper solution not only because of the price of materials for prototype testing but also because of the use of costly machines for this purpose. The virtual machining system can be used independently or as an integral part of advanced CAM systems such as Siemens NX. The study presents an overview and example applications of a virtual high-performance machining system used in the aviation industry (Altintas, 2016).

Latest researches focus on developing methods and strategies that increase the precision of machining, minimizing deformations of thin-walled products and improving fastening technologies to prevent negative impacts of the production process on the final shape of products. These improvements are crucial for the final products to meet the stringent requirements of the aerospace industry. The problem mainly depends on the positioning of the coordinate system from which the next machining process is started. The published works provides a systematic review of cutting technologies for Aerospace Thin-Walled Components (ATWCs), including advanced tooling technology, prediction and control (or suppression) of machined surface integrity, deformation and cutting vibrations, as well as the use of Digital Twin (DT) technology in this process (Li et al., 2024).

Optimization requires dealing with references in the clamping and machining process. Performance aims for data consistency, providing a quick way to establish the defined relative positions of a workpiece in machining space at every stage of its production process. During designing the fastening of elements, a very important is to take into account the deformations of the processed products. The development of intelligent instrumentation that enables to critical process conditions identification, decrease impact of errors or compensation to minimize of defective parts was the subject of the work of a German team, as part of the European research project INTEFIX (2013). One of the milestones of the work concerned the development of instrumentation for identifying and actively limiting vibrations during milling of thin-walled elements. The next stage was related to compensation of workpiece distortions that occur during machining of large, thin-walled structural elements (Möhring & Wiederkehr, 2016).

Studies show that jigs and fixtures are key manufacturing equipment, fulfilling the tasks of positioning, supporting and fastening processed or joined components. A presentation of the current state of the concept of devices and fixtures, their categorization and an overview of their development over the last decade is described in the publication of the work of the WZL and RWTH Aachen University in Germany team (Fiedler et al., 2024).

Often, after machining of an element from semi-finished block e.g. aluminium alloy, it gets deformed after disassembly from the handle or devices. In practice, inception the technological process of production this type of parts is associated with a large number of operations, machining stages and the use of various methods of releasing material stress, which inevitably arise during the removal of the allowance. It is economically unprofitable to use modern machining centers when the processing and setting time is lengthy due to conventional devices usage, which causes processes to be very expensive. Therefore, consideration must be given to the selection of clamping systems and the application of clamping force to the workpiece. Schunk Vero-S Aviation is a specialized system used in the aviation industry for mounting thin-walled, easily deformable parts during machining and assembly (Schiess Vero-S Aviation, 2020).

. This system enables rapid and precise part clamping that allows cycle times reduction and improved accuracy in machining. Schunk Vero-S Aviation offers many different clamping solutions to suit different types of elements. This system uses advanced techniques related to the zero-point concept, which allows for quick and easy exchange of parts. The Schunk Vero-S Aviation system includes elements such as mounting plates, processing tables, mounting screws, as well as various types of mounting tools and accessories. This system is valued in the aviation industry due to its reliability and high quality of workmanship.

In this work, an industrial implementation of Schunk Vero-S Aviation system is presented. This fixture system was selected as a replacement for conventional fixture types such as wedges, clamps, screws. To meet product requirements and reduce general part deformations a strategy of part machining was also taken into account.

2. Experimental

In accordance with the experimental plan, implementation tests were carried out on special product mounting fixtures based on the Schunk Vero-S Aviation system, intended for machining chassis beam parts made of 7075 T6 aluminium alloy, characterized by significant deformations during the conventional milling process. As a result of using this system, an increase in production efficiency and significantly better quality and geometric accuracy compared to traditional clamping were achieved. For example, let us consider the technological process of producing a sensitive part - a chassis beam made of 7075 T6 aluminium alloy at Ultratech, which has significant deformations when processed in a traditional way from a frame.

The Schunk Vero-S Aviation system was used as a clamping system. The main goal was to minimize part deformations during machining, increase cutting performance, efficiency and production costs reduction for one of the major parts of the aircraft - the landing gear beam. In the conventional technological process, the elements were attached directly to the machine table using clamps (Fig. 1). After machining the contour and shape with material removal of up to 4 mm, the cutting process was stopped, the stresses were released - the product was deformed, and the clamps were moved, after which the cutting process was continued. The aim of the test was to develop a clamping method of the product by attaching the parts using 9 modules (Fig. 2).

Machining was simulated in Siemens NX CAD/CAM software by selecting contour machining strategies. The parameters of the process as well as the tools were selected according to previous tests performed on the machine realizing the project.

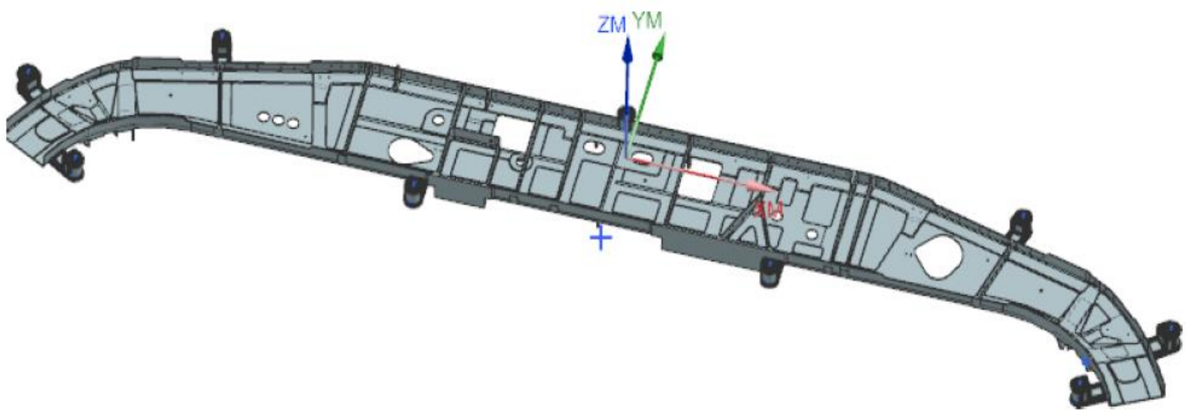

Fig. 1. CAD model of the manufactured part – traditional fixture method.

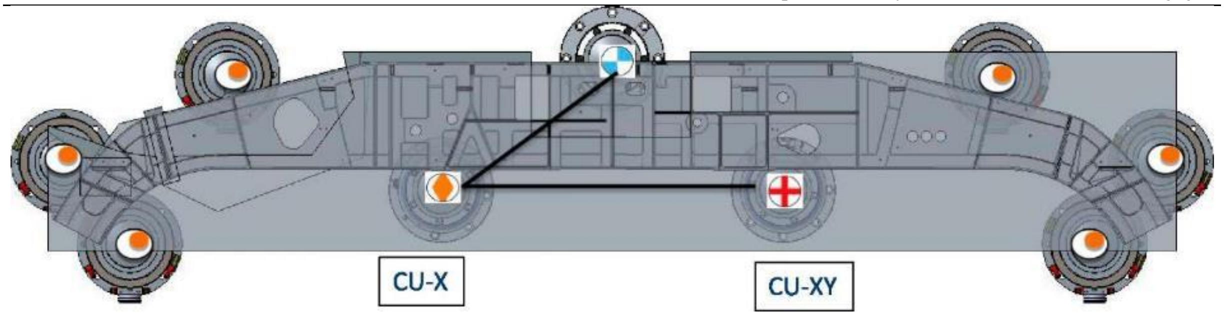

Fig. 2. Developed method of mounting beam-type parts using 9 mounting modules.

3. Results and Discussion

3.1 Comparison of fixture types

Highly efficient milling of thin-walled structural elements made of aluminum alloys using Schunk Vero-S Aviation equipment and lesser extent is a new approach to the production of these parts by milling processes. The use of this technology cannot be compared to milling in special devices or with vices enabling multi-sided milling. Because the first solution is a typical solution for the aviation and space industries solving inter-operational problems of part deformation resulting from the impact of the tool on the workpiece and the release of stresses resulting from the processes of producing semi-finished products. Compared to the current technology used at Ultratech company, we obtained a gain in changeover time of over 30% from the use of these devices (Table 1). In standard processing technology, in order to obtain the flatness of an element of the type presented in the article, the number of reinforcements was 4 and the time of a single changeover was up to 1 hour (setting the piece, using washers, measurements). When producing 2 pieces per month of a given element, in this case this beam, the cost of retooling is relatively high compared to the time required to produce the product individually. Application of Schunk Vero-S Aviation enables reduction of changeovers by up to 30%, using this flexible system, the loosening of the element is automatic and the measurement is made using a probe on a CNC machine. Schunk flexible chuck milling technology solves one of the biggest problems, which is eliminating the risk of human error. Manufacturing such a beam in accordance with tolerances and permissible deformations requires extensive experience of the operator and his cooperation with a CNC programming technologist. In the current traditional method, when retooling an element, the operator should follow the guidelines of the CAM programmer who included the beam fastening elements in his software to avoid collisions during high-performance milling.

Table 1. Benchmarking of used fixture equipment.

Parameter	Detail	Conventional (reference)	Schunk Vero-S1 Aviation
Comparison of unit times (including auxiliary times)	Reduction of changeover time	0%	−70%
Time for a single inter-operation changeover		About 1 hour	Approx. 5 minutes
Automatic loosening of elements and adjustment of the device		No	Yes
Elimination of deficiencies due to instrument	Shortage indicator	About 5%	Less than 1%
Elimination of human errors		No	Yes
Universal solution	Applicable to various products	No	Yes
Reducing the time that it takes for a product to enter the market	Save time and cost in instrument design and manufacturing	4 weeks - 128 hours - average equipment cost 20,000 for a 2.4 meters beam	Yes

Deformations at reference points

Comparison of quality indicators (deformations at reference points and the selected roughness parameter) of machining using traditional clamps - holders and Schunk Vero-S Aviation elements (for the same conditions and machining strategies performed at Ultratech):

1. Traditional clamps.
   Single deformations at the reference points were significant, reaching total values of up to 10 mm. Large deformations are the result of the lack of adequate stabilization and compensation of residual stresses during the machining process, which results in distortions of the finished parts. The allowance for this beam is 3 mm, so in order to produce an element in accordance with the standard, a lot of time must be spent on retooling (adjusting the device and fastening the deformed part for the next operation).
2. Schunk Vero-S Aviation.
   Deformations were minimal, between 0.15 and 1.46 mm, which is half the product approval tolerance. The Schunk Vero-S Aviation system, thanks to advanced clamping technology and stress compensation strategies, effectively reduces deformations, ensuring high machining precision.

Selected roughness parameter (Ra)

Measuring surface roughness after roughing is pointless because chip-breaking tools are used. Surface roughness is measured after finishing machining, where there is no such cutting resistance and machining is less efficient but provides a higher surface quality.

1. Traditional clamps.
   The average roughness parameter (Ra) was approximately 3.2 µm. Higher surface roughness may be the result of unstable mounting and suboptimal processing conditions, which affects the quality of the surface finish.
2. Schunk Vero-S Aviation.
   The average roughness parameter (Ra) was approximately 1.6 µm. Lower roughness indicates better surface finish quality, which is the result of stable fixture and optimized machining strategy, enabling more accurate and controlled surface machining.

The influence of tool vibrations and oscillations

In the case of this type of products, the surface roughness is not as important as the traces of tool vibrations. The main problem when milling aluminum alloys are vibrations of the tool, which affect the quality of the surface finish and may lead to undesirable deformations and reduced machining precision.

1. Traditional clamps.
   Significant tool scatters and vibration led to visible marks on the surface, which negatively affected the quality of the finish and required additional finishing operations.
2. Schunk Vero-S Aviation.
   Reducing vibrations and oscillations of the tool thanks to a more stable mounting allowed for better quality surfaces, minimizing the need for additional finishing operations and improving overall machining precision.

The use of the Schunk Vero-S Aviation system significantly improves the quality of machining by reducing deformation and minimizing traces of tool vibrations (Table 2), which is a key problem when milling aluminum alloys. Thanks to modern technological solutions, it is possible to achieve higher precision, quality of processing and reduced defects, which translates into better quality of finished products and efficiency of the production process.

Table 2. Fixture selection effect on key indicators for machined parts.

Indicator	Conventional	Schunk Vero-S Aviation
Deformations at the reference points of the product measured after complete machining	Up to 10 mm	Below 1.5 mm
Ra – surface roughness parameter	Average 3.2 µm	Average 1.6 µm
Traces of vibrations	Significant	Not significant

The main features of the tooling and milling technology in Schunk Vero-S Aviation holders are as follows:

1) Up to 95% of the metal volume is removed at the lowest possible number of settings.
2) Compensation of thermal expansion of workpieces and internal stresses without the use of washers and clamps, and at the same time eliminating human errors and related costs.
3) Positioning repeatability between roughing, finishing and control passes.

4) A new technological machining process that significantly reduces the time required for setting and milling elements.

The instrumentation can be adapted to changes in the shapes of individual products very quickly and while keeping the basics intact - bases, zero points, without making expensive adjustments or adapting existing ones.

3.2 Machining details with Schunk Vero-S Aviation

Roughing was performed by milling in two operations (OP10, OP20). Finishing was performed on a specially designed vacuum device due to the very thin bottom of the product - 1.5 mm in the center of the part. The total height of the blank was 114 mm.

3.2.1. Fixture 1 - Milling operation OP10

The completed semi-finished product and the prepared fastening elements were mounted on a FIDIA multi-axis CNC machine (Fig. 3). OP10 machining programs were created in the Siemens NX CAM system and a test element was machined then measurements were made using a measurement probe on a CNC machine. The element was measured at individual points marked in the technical drawings.

Fig. 3. Developed method of mounting the blank on a CNC machine in OP10.

Milling strategy:

1) Pre-milling 20 mm from the upper reference surface:
   tool ⌀20 mm, R = 3 mm - S-Carb APR-3 Kyocera SGS Precision Tools,
   v_c =1380 m/min, f_z = 0.08 mm/tooth,
   Stress release - loosening fasteners.
2) Pre-milling 20 mm of the outer contour:
   tool ⌀20 mm, R = 3 mm - S-Carb APR-3 Kyocera SGS Precision Tools,
   v_c = 1380 m/min, f_z = 0.08 mm/tooth,
   Stress release - loosening fasteners.
3) Pre-milling of 47 mm pocket and contour:
   tool ⌀20 mm, R = 3 mm - S-Carb APR-3 Kyocera SGS Precision Tools,
   v_c = 1380 m/min, f_z = 0.08 mm/tooth,
   Stress release - loosening fasteners.
4) Pre-milling 20 mm of the outer contour:
   tool ⌀20 mm, R = 3 mm - S-Carb APR-3 Kyocera SGS Precision Tools,
   v_c = 1380 m/min, f_z = 0.08 mm/tooth,

A 6 mm of material was left on the outer contour (an allowance), without cutting the contour along its entire height (Fig. 4).

The measurements were made using an workpiece probe in the spots indicated in the Fig. 5, at points M1 and M2, after each milling operation and releasing the handles (1-4). The measurement results are presented in Table 3. The results were summed up to give the final dimension of the element's deformation from the reference point in the Z axis of the machine tool.

Fig. 4. Milling test performed on the CNC machine - operation OP10.

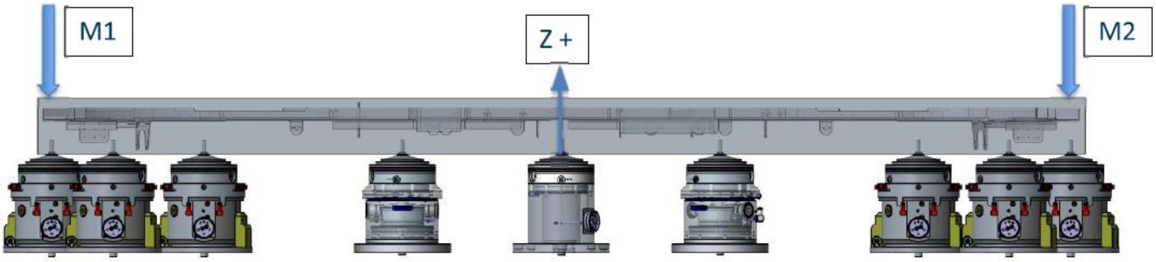

Fig. 5. Scheme of mounting the element in a side view and measuring the height of the element on the machine tool - after the OP10 operation at points M1 and M2.

Table 3. Results of element deviations in individual cuts after OP10 operation.

Measurement step	Measurement value at point M1, mm	Measurement value at point M2, mm
1	0.31	0.42
2	0.25	0.38
3	0.78	0.8
4	0	0
Total	1.34	1.6

3.2.2. Fixture 2 - Milling operation OP20

Figure 6 presents mounting for OP20. For this purpose, machining programs were created in the Siemens NX CAM system and a test element was machined while measurements were made using a workpiece probe on a CNC machine. The element was measured at individual points marked in the technical drawings.

Fig. 6. Developed method of mounting an element on a CNC machine in OP20.

Milling strategy:

1) Pre-milling 25 mm from the upper reference surface:
tool ⌀20 mm, R = 3 mm - S-Carb APR-3 KYOCERA SGS Precision Tools,
v_c = 1380 m/min, f_z = 0.12 mm/tooth,
Relieving stress - loosening fasteners
2) Pre-milling 22 mm of pocket and contour:
tool ⌀20 mm, R = 3 mm - S-Carb APR-3 KYOCERA SGS Precision Tools,
v_c = 1380 m/min, f_z = 0.12 mm/tooth,
Stress release - loosening fasteners.
3) Pre-milling 20 mm of the outer contour:
tool ⌀20 mm, R = 3 mm - S-Carb APR-3 KYOCERA SGS Precision Tools,
v_c = 1380 m/min, f_z = 0.12 mm/tooth,
Stress release - loosening fasteners.
4) Pre-milling of a 20 mm pocket:
tool ⌀20 mm, R = 3 mm - S-Carb APR-3 KYOCERA SGS Precision Tools,
v_c = 1380 m/min, f_z = 0.12 mm/tooth,
Stress release - loosening fasteners, zero-point shift + 3 mm.
5) Finish milling 3 mm from the product contour:
Tool ⌀12 mm, R = 3.2 mm - S-Carb APF-3 KYOCERA SGS Precision Tools,
v_c = 600 m/min, f_z = 0.08 mm/tooth,
Stress release - loosening fasteners.
6) Finish milling 1 mm from the product contour:
tool ⌀12 mm, R = 3.2 mm - S-Carb APF-3 KYOCERA SGS Precision Tools,
v_c = 600 m/min, f_z = 0.08 mm/tooth,
Stress release – zero-point shift +1 mm.

The finished part in operator OP20 (Fig. 7) has been submitted for verification. The measurement was made using a workpiece probe in the places indicated in the diagram below (Fig. 8), at point M1 and M2, after each milling operation and releasing the handles (1-6). Measurement step 7 was to completely release the piece from the holders. The measurement results are presented in Table 4. The results were summed up to give the final dimension of the element's deformation from the reference point in the Z axis of the machine tool.

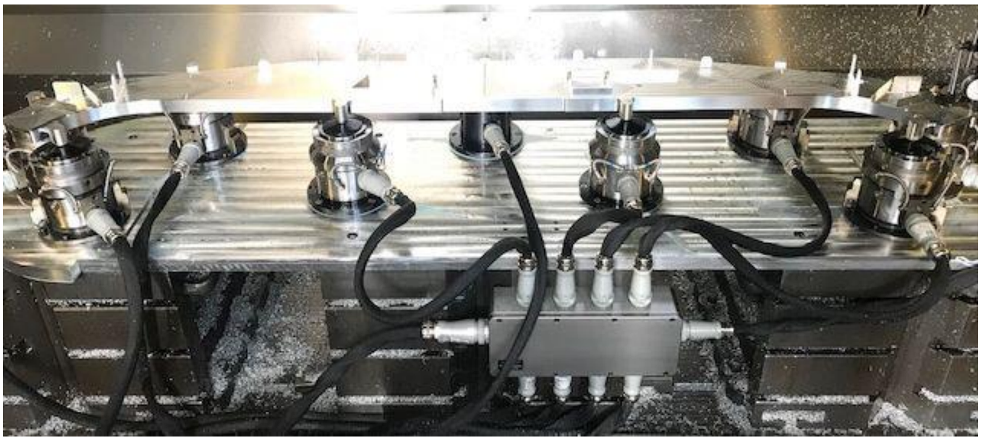

Fig. 7. Milling test performed on the CNC machine - operation OP20.

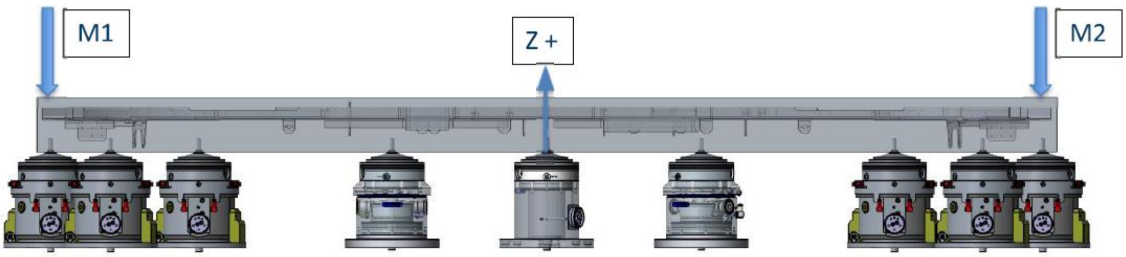

Fig. 8. Scheme of mounting the element in a side view and measuring the height of the element on the machine tool - after the OP20 operation at points M1 and M2.

Table 4. Results of element deviations in individual cuts of OP20 operation.

Measuring step	Measurement value at point M1, mm	Measurement value at point M2, mm
1	0.39	0.79
2	3.7	4.45
3	0.05	0.4
4	1.4	1.85
5	0.75	0.45
6	1.1	0.9
7	0.8	0.8
Total	8.19	9.64

The purpose of the measurement was not to control the dimensions of the part, but to check whether the value of deformation (product deformation) after the machining operation would not be greater than the allowance left for the next operation - machining. The measurement is made only in the Z axis, because in this case the most important thing is to maintain the wall thickness at the bottom. In the event of a deformation greater than the expected allowance after rough machining, subsequent machining, after loosening the fasteners and allowing the product to deform, will lead to piercing/milling of the bottom of the structural element and will result in part being a scrap.

3.2.3. Fixture 3 - Milling operation OP30

For the third operation (OP30), the element was mounted as shown in Fig. 9. OP30 machining programs were created in the Siemens NX CAM system. The test part was manufactured and then measured with a workpiece probe on the CNC machine. The element was measured at individual points marked in the technical drawings. The element was mounted on a specially designed vacuum jig.

Fig. 9. A developed method of mounting an element on a CNC machine in OP30.

3.2.4. Finish milling strategy

Finishing contour milling in just a few steps. Since the OP30 was performed on a vacuum jig, the details of the subsequent operations were not described, as this was the finishing of the product and it did not have such an impact on the deformation of the product. For finishing operations, cylindrical face mills were used in the diameter range from 20 mm to 8 mm, depending on the geometry of the model (radius of rounding of the product).

After unfastening the mounting clamps (standard claws), the part (Figs. 10 and 11) was deformed by approximately 1 mm in the Z axis. Finally, the achieved part deformation was measured (Fig. 12) and deviations met the range of requirements, 3 mm tolerance band.

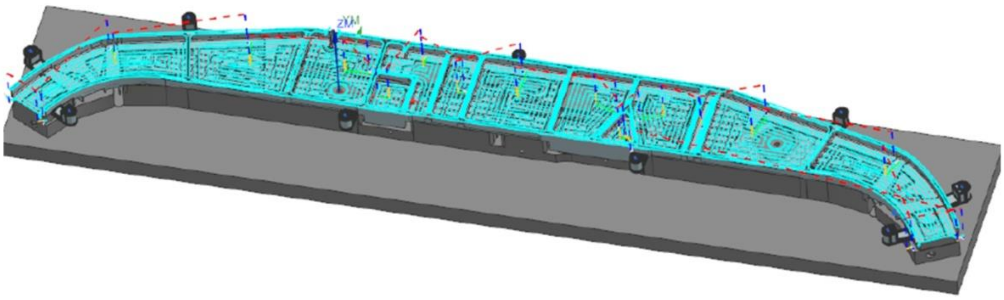

Fig. 10. View of toolpaths finish milling operations performed on a vacuum fixture in NX CAD/CAM.

Fig. 11. Machined part by the CNC machine - operation OP30 - side view of the element.

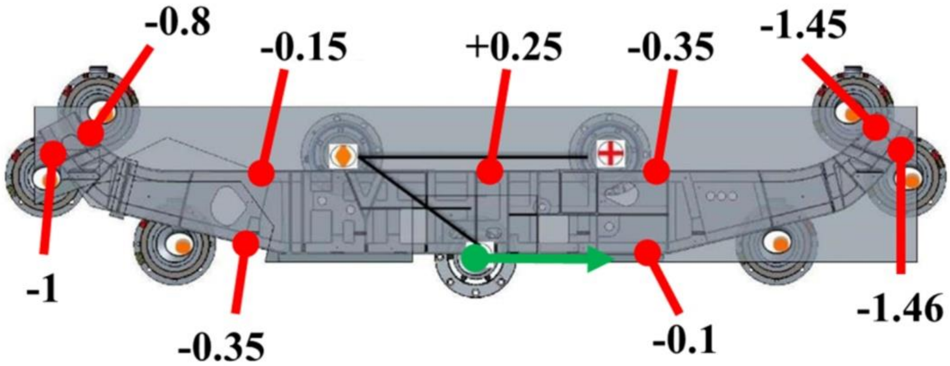

Fig. 12. Final measurement results of manufactured part after unclamping from the fixture.

The proposed Schunk Vero-S Aviation mounting system significantly contributes to achieving acceptable results by reducing deformation, reducing oscillations and vibrations, optimizing the machining process, improving roughness parameters and reducing production costs. These benefits translate into higher quality and efficiency in the production of unstable aluminum parts, meeting the requirements of the modern aerospace industry and other industries requiring precision machining.

In standard milling with positioned workpiece using special devices such as a frame or clamps (to have access to the processing of both sides of the part), after complete milling and removing the element from the device, the element is deformed, and the deformations reach up to several millimeters or centimeters depending on the dimensions product (beam) ranging from 0.5 to several meters. In most cases, due to the lack of experience of the manufacturing team, the milled product does not pass quality control. Due to costs, this element is stretched, bent and straightened to meet the acceptance requirements, but this must require the recipient's acceptance. As this element is a structural element, assembled by hand using riveting techniques, slight deformations are allowed for this 2.4 meter long beam tested, with a maximum deformation of 3 mm allowed, assuming that installers are able to fasten and adjust the element by hand during installation usually riveting process. Multi-axis high-performance milling technologies are also used in vices, gripping the base of an aluminum block, which is connected to the product using additional bridges cut off in the final operation. Due to the local mounting of the product in relation to the frame, the entire product is deformed, which causes subsequent operations to mill the deformed product according to the CAM program - a 3D model that does not take into account its deformation, thus causing a shortage. There is research on predicting these deformations and adapting appropriate 3D models to perform the technological process in a CAM system. Unfortunately, changing 3D models in this way is very complicated. The tested solution does this automatically, loosening the product between operations, giving it free to deform. Finishing was performed on an element that is no longer subject to further deformation.

Machining techniques and the technological history of semi-finished products influence the deformations of thin-walled elements made of aluminum alloy after milling. Milling in the direction perpendicular to the rolling direction results in larger deformations than milling in the parallel direction (Zawada-Michałowska et al., 2020a). The initial residual stress in the blank is a major factor leading to machining deformation, and uneven milling during the machining process, caused by the variation in local cutting depth resulting in uneven material removal thickness, contributes to machining deformation (Zheng et al., 2023).

Avoiding deformation in aluminum elements can be achieved through the optimization of milling parameters, selection of appropriate milling strategies, and control of machining conditions. Analysis of the influence of milling parameters on milling forces, milling temperature, and machining deformation has shown that the optimized milling parameters are able to be determined, which significantly reduce machining deformation and improve the machining quality of thin-walled parts (Yang et al., 2022). It was found that post-machining deformation of thin-walled elements can be minimized by using a selected milling strategy and its combination with pre-machining (or lack thereof) (Zawada-Michałowska et al., 2020b). The other results indicates that post-deformation annealing to increase ductility suggests a potential approach for minimizing deformation (Zrník et al., 2014).

4. Summary

In the current scientific publication, the key was to analyze in detail the occurrence of deformations during the machining process of thin-walled structural component. Deformations of approximately 1.6 mm were observed in OP10 operation and identified to be as expected and considered acceptable. This happens due to the stresses of the part caused by the forces, which are typical to roughing operations when machining this kind of thin-walled part. Additionally, the direction of the shift was consistent with the predictions, which confirms the correctness of the machining strategy used at this stage.

Much greater challenges were encountered when milling the other side of the part, where deformations of 9 mm in one direction were observed. Such a large deviation from the predicted values was not expected and indicates potential problems with the milling process, which may require further analysis and technological optimization. A deviation of 9 mm is the total value of individual deviations in each milling operation in the OP20 fixture. The analysis requires looking at individual milling operations, i.e. machining parameters and the resulting deformation of the part. The solution to these situations is either to reduce the machining parameters of cutting speed and feed, which will adversely affect the machining time, or to increase the allowance remaining for subsequent milling operations. Increasing the allowance will increase the thickness of the product, which may reduce its deformation. After the third operation (OP30) was measured and the deformation values of the entire product were given and are within its manufacturing tolerance of 3 millimeters. The fact that the element was partially deformed during individual operations and the handle adapted to the deformed element and was reattached, after which it was processed. This value of 9 mm is the predictable total deformation value of the element in the event that we did not loosen the handles for subsequent operations and the handles did not adapt to this part.

In operation OP20, which included the finishing process, further deformation and movement of the component was observed. This type of movement occurring during the finishing stage is usually undesirable as it can significantly affect the quality of the final product. Normal process conditions should not lead to any displacement, so these results suggest that there is a need to review and potentially revise both the clamping method and the machining process parameters. Tests showed that the fastening system was operated close to the limits of its maximum movement capabilities (+/- 6 mm). In response to this, an additional pad was added for the pin extensions, which increased the Z-direction movement capabilities on the four 3D modules at the end of the part. This step was necessary to provide greater flexibility and precision in the final stages of machining.

The main purpose of using the proposed Schunk Vero-S Aviation fastening system was to minimize the deformation of the product after processing in individual operations. The measurement results of the final product after operation OP30 confirm the advisability of this use. Traditional fastening methods often lead to significant deformations, which results in parts failing quality control and requiring costly and labor-intensive manual corrections. The Schunk Vero-S Aviation system is designed to provide a more stable fixture that allows parts to move freely between operations, minimizing stress accumulation and reducing deviation, resulting in higher machining precision and better-quality finished products. The purpose of this test was to show how large element deviations can be during high-performance milling of thin-walled structural elements. Despite the deviations between operations, thanks to this system which adapted to the deformed product and stabilized it by appropriately fixing it for further operations.

Thanks to the use of this system, we avoided to achieve scrap part which can be caused by the fact that the thickness of the bottom of the beam was 1.5 millimeters, and after milling and measuring the product, analyzing the allowances left, we came to the conclusion that it was necessary to shift the coordinate system for NC code for the workpiece on CNC machines to maintain this thickness of the bottom of the beam. Hence, in the second operation OP20 there is an entry about shifting the zero (coordinate system) by one millimeter.

5. Conclusions and feature prospects

The experiments performed show that both the tools and cutting parameters were appropriately selected and did not negatively affect the deformation of the parts. This indicates their application in the context of the processing methods used in CAM software for thin-walled parts. These results highlight the importance of continuously monitoring and adapting machining techniques and fastening methods to minimize the risk of deformation and ensure high quality of final products, especially in the context of demanding industrial production.

The most important point for the future of component production is to reduce the deformation in the OP20 operation and allow the part to move more freely in the OP10 operation.

- Process the material as much as possible in OP10, one of the keys one's points will be to machine the outer contour along the entire height of the board in OP10 was recommended.
- Quality check of the raw material - semi-finished product.

An alternative strategy option could be to machine the part in 4 operations:

- OP10 - milling of the first side (clamping side for vacuum equipment) and complete outer contour throughout,
- OP20 - milling the second side with an allowance of 5-6 mm,
- OP30 - finishing the first side of the part on VERO-S Aviation,
- OP40 - finishing the other side on the special fixing vacuum jig.

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Wdrożenie Technologii Wysokowydajnego Frezowania Stopów Aluminium z Wykorzystaniem Innowacyjnych Narzędzi i Oprzyrządowania

Streszczenie

Badania opisane w artykule dotyczą rozwoju i wdrażania nowych technologii mocowania stosowanych w obróbce skrawaniem, szczególnie w przypadku cienkościennych elementów konstrukcyjnych samolotów i śmigłowców. Przeanalizowano m.in. wydajność systemu mocowania Schunk Vero-S Aviation w obróbce belek podwozia ze stopu aluminium 7075 T6, co umożliwiło w znacznym stopniu wzrost wydajności produkcji i poprawą jakości geometrycznej obrabianych części. Podczas badań eksperymentalnych i testów wdrożeniowych zastosowano specjalne uchwyty w systemie Schunk Vero-S Aviation do obróbki belki podwozia. Wyniki wykazały poprawę jakości i dokładności obrabianych części w porównaniu z tradycyjnymi metodami mocowania. Zwiększona wydajność produkcji poprzez zminimalizowanie ilości odpadów w postaci braków i znacznie lepszą jakość powierzchni po frezowaniu, oraz właściwości geometryczne w porównaniu do konwencjonalnego mocowania za pomocą zacisków czy imadeł. Badania te zostały przeprowadzone w ramach projektu przez firmę Ultratech Sp. z o.o., która realizowała projekt dofinansowany z Funduszy Europejskich "Opracowanie i wdrożenie innowacyjnej metody mocowania do obróbki frezarskiej cienkościennych elementów konstrukcyjnych helikopterów i samolotów".

Słowa kluczowe: części niesztywne, element cienkościenny, stopy tytanu i aluminium, wysokowydajne frezowanie