Method of controlling the lead angle of the toroidal cutter axis in 5-axis machining of the turbine blade

Metoda sterowania kątem prowadzenia osi frezu w pięcioosiowej obróbce łopatki turbiny

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Presented is the own concept control method an lead angle axis of the toroidal cutter, depending on the radius of curvature of the machined sculptured surface profile. The method verified on the example machining of the turbine blade. In order to compare the effects of this method, to the classical method (without adaptation lead angle), tests were performed for both these methods.
KEYWORDS: 5-axis machining, sculptured surfaces, turbine blade

Five-axis milling with a toroidal milling cutter is widely used in machining composite surfaces such as turbine blades [1-3]. This multi-axis machining method, by combining three linear displacements and two additional rotary ones, enables the tool to move in space continuously with respect to the normal vector to the machined surface. This process is technologically allows for [2]:

- obtaining high quality surfaces by selecting the best contact conditions between the tool and the work surface,
- reduction of processing time by using a suitable tool geometry to the work surface, thus increasing cutting width.
- increase in machining efficiency and tool rigidity by reducing its reach.

In industrial practice, the basic (classical) machining strategy for turbine blade parts is simultaneous, five--axis face milling with a constant angular axis of toroidal milling, irrespective of the radius of curvature ρ_{1n} (fig. 1) [1]. One of the main problems is the selection of the orientation of the tool axis relative to the actual curvature of the profile of the work surface [3, 4, 6].

The guide angle value of the toroidal milling cutter is defined at the CAM machining programming stage with respect to the vector of the normal machined surface. The main disadvantage of this strategy is the failure to take into account the continuous variations in the curvature radius ρ_1 of the surface profile to be processed. This results in continuous changes in the cross-section of the cutting layer, which results in continuous changes in the

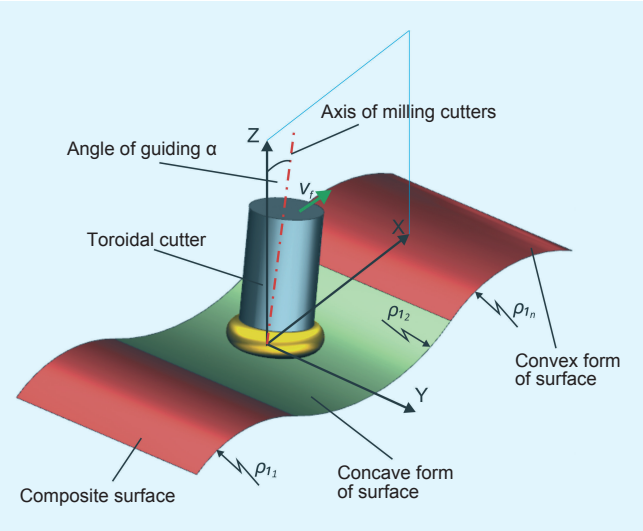

Fig. 1. Five-axis face milling of composite surfaces

component values of the cutting force and the direction of their operation. This leads to the variable elastic deformation of the tool and the workpiece, the shape of errors and increase in surface roughness [2].

This paper presents a new concept of adaptive method (strategy) of five-axis milling of composite surfaces, which was used for turbine blades machining.

Adaptive five-axis turbine blades machining

The concept of adaptive methods five-axis machining complex surfaces shown in fig. 2. The illustrated box tool (milling cutter toroidal) and its position relative to the workpiece (turbine blade).

The turbine blade (1) is mounted in the jaws of the divider (8) for the rotary motion of the controlled axis *A*. The divider is located on a table of a five axis milling machine which implements the controlled linear axis *Z*. The longitudinal axis (2) of the workpiece is parallel to the controlled axis *X*, while the cross-sections of the blade lie in parallel planes (7) to the *ZY* plane.

Toroid cutter (4) is fixed in the spindle five-axis milling machine, which performs a rotational movement driven axis B. In the initial position the rotation axis of the milling cutter (5) remains parallel to the *Z* axis while

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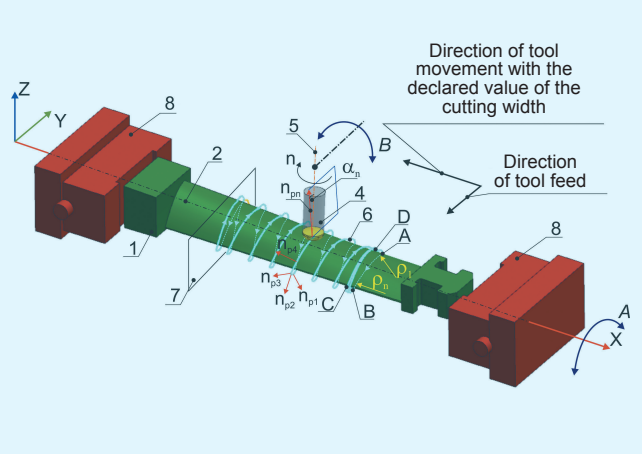


Fig. 2. Adaptive strategy of five-axis blade machining

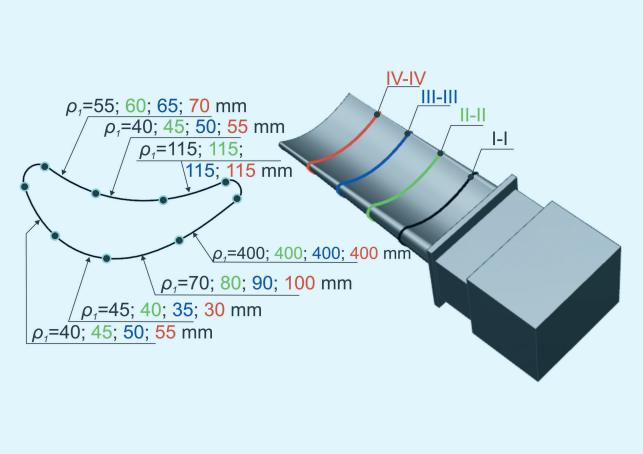


Fig. 3. Model of turbine blade

moving the working axis is oriented in space relative to the normal vector to the workpiece n_{pn} curved surface. The cutter toroidal working traffic moves in a five-axis trajectory (6) relative to the normal vector of the surface being machined n_{pn} adaptation parameter αn lead angle, depending on changes in the radius of curvature of the workpiece surface profile ρ_n. The value of this angle is selected using the procedure as described in [1, 2].

During machining, the toroidal milling cutter (4) moves relative to the workpiece (1) in such a way that it traverses a section of the five-axis trajectory (6) between points *A* and *B* with adaptation of the guiding angle parameter: α_1 for the radius ρ_1, αn for the radius ρ_n, Then, from point *B*, it crosses a segment of the five-axis trajectory (6) with a constant angle of rotation of αn, moving simultaneously with a working motion equal to the declared cutting width to point *C*. From this point, the toroidal milling machine (4) Adaptation of the angle of the guide angle αn, and then from the point *D* overcomes the section of the five-axis trajectory (6) with the constant value of the angle α_n, moving simultaneously with the working movement by the section equal to the declared cutting width to the next point from which the whole cycle of milling movements (4) is repeated from the beginning.

Experimental verification of the method

To verify the effects of the proposed method, the turbine rotor blade was treated with a classical strategy (without adaptation of the α angle) and adaptation strategy (with α angle adaptation). Verification model of turbine impeller was modeled on four sections of pen profile (I-I÷IV-IV). These sections were formed from arcs with different radii of curvature ρ_1 (fig. 3).

The blade was machined using a five-milling 100 DMU Mono-Block milling center (fig. 4).

For the verification tests, the toroid cutter R300--016B20L-08L Sandvik Coromant and round cutting inserts R300-0828E-PL carbide S30T, were used. The turbine blade was made of Inconel 718. The cutting parameters were determined based on the manufacturer's recommendations for the test tool (Table I).

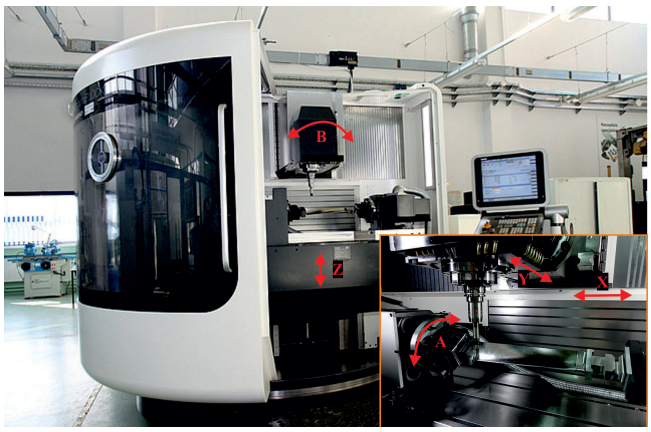


Fig. 4. Five-axis milling center 100 DMU MonoBlock

The criterion and the limitation of the selection angle *α* are shown by the dependencies, which are summarized in the Table II.

The measurements of the Δ_k shape and *Ra* surface roughness parameters were verified in the verifiable sections of the blade profile. These measurements were

TABLE I. Cutting parameters according to toroidal milling manufacturer's recommendations

Parameters	Machining of concave and convex surface of turbine blade
Axial infeed a_p	0,25 mm
Radial infeed a_e	1,5 mm
Feedrate per blade f_z	0,26 mm/blade
Cutting speed v_c	40 m/min

TABLE II. The assumed values of the shape deviation Δ_k and *Ra* parameter of the surface roughness

	Turbine blade concave side	Turbine blade convex side
Criterion	$\Delta_k \leq 0{,}025$ mm	$\Delta_k \leq 0{,}040$ mm
Restriction	$Ra \leq 0{,}45$ µm	$Ra \leq 0{,}55$ µm

carried out using the Accura II Zeiss coordinate measuring machine (fig. 5a) and the MahrSurf XR 20 profiler (fig. 5b).

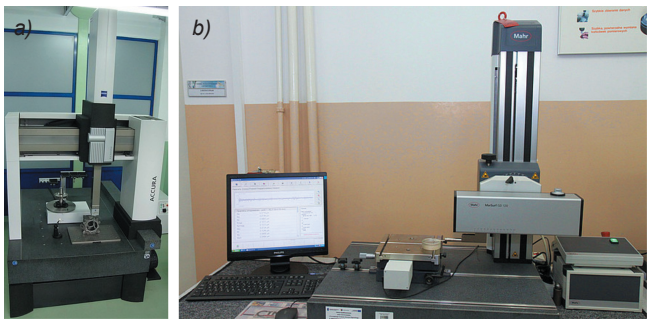
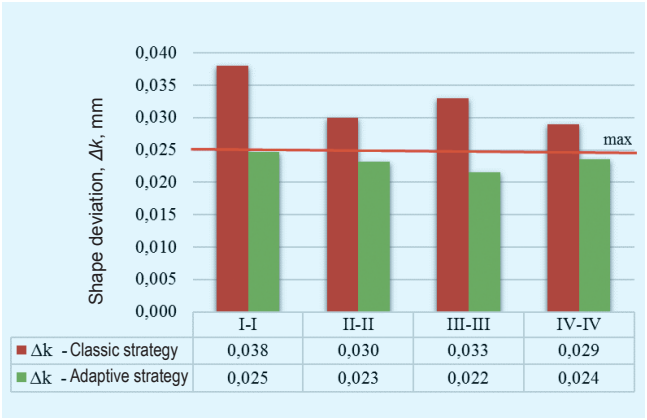


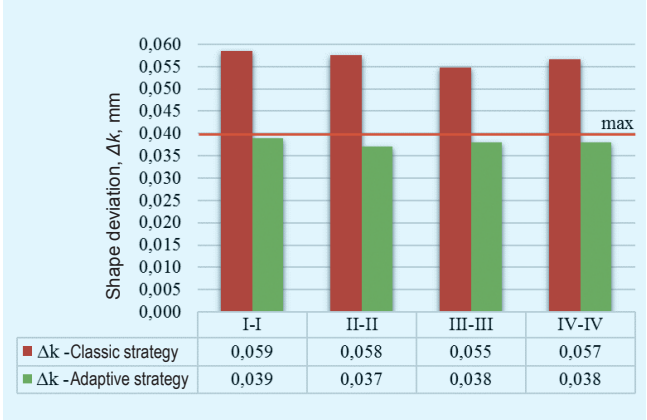
Fig. 5. Device used for testing: *a*) coordinate measuring machine Accura II Zeiss, *b*) MahrSurf XR 20 profilometer

■ **Deviation of shape.** The results of measuring the shape deviations Δ_k analyzed transverse sections of the blade airfoil illustrated in fig. 6 and fig. 7.



	I-I	II-II	III-III	IV-IV
Δk - Classic strategy	0,038	0,030	0,033	0,029
Δk - Adaptive strategy	0,025	0,023	0,022	0,024

Fig. 6. Deviations of the Δ_k shape of the analyzed profiles of the concave side of the blade



	I-I	II-II	III-III	IV-IV
Δk - Classic strategy	0,059	0,058	0,055	0,057
Δk - Adaptive strategy	0,039	0,037	0,038	0,038

Fig. 7. Deviations of the shape Δ_k of the analyzed profiles of the convex blade side of the blade

■ **Surface roughness.** Mean values of the parameters *Ra* surface roughness of the concave side is shown in fig. 8. In contrast, mean values of the surface roughness *Ra* of the convex side of the vane shown in fig. 9.

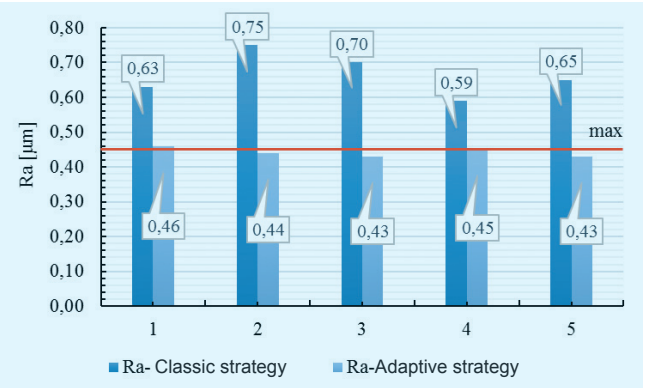


Fig. 8. *Ra* surface parameters of the concave surface side

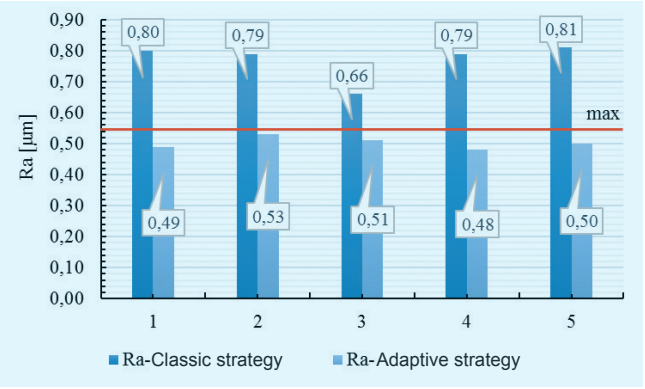


Fig. 9. *Ra* surface parameters of the convex surface side

Conclusions

As a result of the proposed new control method (adaptation), the angle of rotation α, depending on the variation of the curvature radius ρ_1 of the surface profile being processed, reduced the deviation of the blade shape Δ_k in the range of 25÷30% with respect to the treatment of the same pen with a classical strategy (without adaptation of the angle α). In addition, the Ra value was reduced and their distribution evenly distributed on the treated surface.

In conclusion, it can be stated that the developed concept of the angle control method of guiding the axis of the toroidal milling machine increases the accuracy of the five axis machining of composite surfaces.

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