Modern technology of the turbine blades removal machining

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Abstract: Modern technology of the turbine blade and vane removal machining was discussed. The nowadays abrasive machining technologies and the machine tools for this purpose and their character and advantages were described. The current turbine blade manufacturing trends based on the HSCD grinding method were discussed. The applications of the different types of the abrasive tools for the turbine parts production were given. The unconventional technologies for the turbine blades manufacturing were described.

Key words: aerospace technology, abrasive machining, grinding wheel, machining centre, turbine blade, unconventional methods of machining.

1. Introduction

The advanced aero-engine materials such as superalloys, titanium and its alloys, alloys of nickel with aluminium, [22, 24-26], stainless steel found wide application in the turbine parts manufacturing. The novel structural materials [1-2] as well as the jet-engine components after their surface layer modification [3-4] are harder and harder to machining. The turbine components such as: the turbine blades, turbine vanes, turbine vane rings, turbine nozzles (vane segments), engine and turbine casings needs employing the advanced manufacturing technologies and the modern machine tools and equipment, the suitable cutting and abrasive tools [5-6, 26], as well as appropriate CNC control systems and software [26]. The difficult-to-machine materials used in aviation and space engineering require especially the new technology of machining and the suitable tools and the machine tools implementation to increase grinding capacities, to lower manufacturing costs per piece, to secure reproducibility of the products quality and to secure the safe conditions of work for an operator [7, 9, 11-25, 27].

Technologies of the turbine components manufacturing comprise: broaching, milling, grinding with the grinding wheels, grinding with the abrasive belts, deburring with the abrasive brushes and unconventional technologies in the turbine blades and blisks machining (Abrasive Water Jet Machining – AWJM, Abrasive Flow Machining – AFM, Electro-Chemical Machining – ECM, Electro-Discharge Machining – EDM).

High-speed cutting (HSC) permits stress-free sculptured machining of the high performance alloys and composites being used by aircraft and power-generation manufacturers [26]. The multi-axes CNC machining centres guarantee a high level of shape repetition accuracy in series production.

A cost-efficient alternative to milling is high efficiency grinding (Table 1). Development works on technologies of high volume grinding variations have been carried out for over 35 years [24-25].

In the high-speed grinding technologies are achieved machining capacities 10÷20 times greater than milling and 100÷1000 times greater in comparison with conventional grinding. The following high-speed grinding parameters are used [12-19, 24-26]: grinding wheel peripheral speed (i.e. cutting speed ) from \( v_s = 60÷125 \) m/s for the vitrified grinding wheels and \( v_s = 80 \) to \( 250÷300 \) m/s for the cubic boron nitride (cBN) or diamond grinding wheels with galvanic bond; grinding wheel or table feed speed \( v_f \) from \( 1÷10 \) m/min; infeed \( a_p \) (depth of grinding) up to \( 30 \) mm; pressure of a coolant delivery from 0.5÷6.5 MPa; the coolant output \( 10 \) dm\(^3\)/min per 1 mm active grinding wheel width and \( 200÷400 \) dm\(^3\)/cm\(^2\) workpiece material being ground during 1 min.

For high efficiency grinding of the products the grinding wheels made of superhard materials are used in particular, beside wheels made of traditional abrasives.

Beside of the conventional electroplated grinding wheels with 40% protrusion of the cBN or diamond grain, a metal single layer (MSL) grinding wheels in which about 60% of the diamond or cBN grain is exposed, are used in HEDG grinding also. The benefit of the plated wheel is that the wheel can have any machinable complex shape, eliminating dressing, but a high price of that wheel type is a disadvantage, when comparing to an aluminium oxide conventional wheel.
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2. Turbine components machining

The turbine components machining by broaching [6, 27] is an older technology of manufacturing the turbine disk root mounting slots and the turbine blades root profile (Fig. 1). There is a possibility to manufacture by broaching complex slot in only one stroke, with roughing and finishing operations, within geometrical size accuracy of ~ 0.010 mm and surface roughness Ra ~ ≤ 0.002 mm. The broaching process itself, once in production, is fast and efficient, but there are some aspects of the process, which make broaching a very expensive and time consuming process, such as:

• the purchase price, maintenance cost, floor space requirements and long lead-time of broaching machines;
• the special concrete base and other infrastructure to support broaching machines;
• the purchase price, maintenance cost (resharpening and inventory) and long lead-time of broach tools;
• the time required to set up and change over broach machines for different part numbers;
• high cutting forces (up to 10,000 N) and low broaching speeds (2 m/min in heat resistant steels) [6].

<table>
<thead>
<tr>
<th>Process</th>
<th>Process parameters (infeed, feed speed, cutting speed)</th>
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<tr>
<td>Reciprocation grinding SFG</td>
<td>$a_p = 0.001 \pm 0.1$ mm; $v_f = 1 \pm 30$ m/min; $v_c = 20$ m/s</td>
</tr>
<tr>
<td>Deep grinding DCG</td>
<td>$a_p = 0.1 \pm 30$ mm; $v_f = 0.01 \pm 2$ m/min; $v_c = 20 \pm 30$ m/s</td>
</tr>
<tr>
<td>CFG (Creep Feed Grinding)</td>
<td>$a_p$ up to 30 mm; $v_f = 1 \pm 10$ m/min; $v_c = 60 \pm 125$ m/s (for the vitrified grinding wheels); $v_c' = 80$ up to 250-300 m/s (for the cBN or diamond grinding wheels with galvanic bond)</td>
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The obtained highest material removal rates per unit active grinding wheel width $Q_w''$ are [16-19, 24-26]:
- for the conventional grinding wheels with vitrified bond $Q_w'' = 10 \pm 100$ mm$^3$/mm$^3$s
- for the cBN grinding wheels and with bond: resinous – $Q_w'' = 50 \pm 150$ mm$^3$/mm$^3$s; vitrified – $Q_w'' = 50 \pm 150$ mm$^3$/mm$^3$s, but grinding wheel peripheral speed is higher in comparison with resinous bonded wheels; metal – $Q_w'' = 50 \pm 250$ mm$^3$/mm$^3$s; galvanic – $Q_w'' = 1,000 \pm 10,000$ mm$^3$/mm$^3$s

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Figure 1. Turbine components broaching: a – the turbine disk with root forms being traditionally manufactured by broaching [26-27], b – a series of the broach tools is used to complete the entire root fir tree profile [26-27]

In the modern aero jet engines, the various turbine components are manufactured from a forging, as the turbine blades and vanes or machined from one solid piece of material, e.g. turbine rotors, impellers and bladed disks, which are called blisks [26] or Integrially Bladed Rotors (IBRs) [26]. The most difficult tasks for machining are the blade roots and the aerofoils sculptured surfaces shaping.

Figure 2. Turbine blades machining on the Starrag machining centres
a – the blade clamped on HX 351 machining centre of Starrag [27], b – the blade aerofoil five axes machining [27], c – the blade root machining [27], d – view of the StarragHeckert center STC 630 D [27]
The modern 5-axes machining centres enable machining of the turbine and compressor blade leading edges, trailing edges and tips in one set-up operation (Fig. 2a). In Fig. 2 are shown the examples of the blade’s aerofoil (Fig. 2b) and root (Fig. 2c) machining. The centers of STARRAG are equipped with CNC control system with software for NC simulation of the blade aerofoil and the blade root machining process, enabling the operator to check milling operations and tools on the computer screen and optimize the NC program.

The finish grinding of the blade aerofoil surface have been impossible on those machine tools however. The blades needed extensive hand-polishing to generate the required shape and surface roughness.

The machine tool producers developed the other type of the machining centres, connecting in one machine features of the milling and grinding machines, to avoid those disadvantages and to reduce the number of the necessary machine tools.

3. Turbine blades machining and grinding

Nowadays in the different technologies of the turbine blade and vanes removal machining the machining centres (Makino A99-5XR-CD, Bridgeport FGC 1000) are applied by the producers. These centres were adopted by modernization to grinding the blades with VIPER method (an acronym of Rolls-Royce: Vitreous Improved Performance Extreme Removal), however their main purpose were machining with the cutting tools of defined edges geometry.

The modernization included accommodation to the conditions of grinding: the main spindle, the splash guards of roller rail linear movements, a cooling medium delivery and filtration unit, an adequate type of coolant selection, equipping the machine tool with grinding wheel dressing attachment and with numerically controlled system of the nozzles to deliver the coolant directly in-to the machining zone, to work out a suitable software for CNC control system.

The other examples of the modernized machine tools for turbine blades are machining centres of Mägerle: C40 – accommodated to ‘Diati’ process of Raysun and MFP 160-50 – accommodated to grinding with vitrified grinding wheels and with cBN wheels (Fig. 3a-c). The centres are equipped with the shaped grinding wheel rotary drum or chain style storage magazines.

![Figure 3](image-url)

Figure 3. The example of flexible centres used for turbine blades and vanes grinding:

a – front view of Mägerle MFP 50 centre for profile grinding and CFG, drilling and turning [8],
b – view of Mägerle MFP 50 centre’s the grinding wheel rotary drum style storage magazine with a new tool changer [8, 27],
c – the turbine blades grinding on a Mägerle CF machine [8, 27],
d – comparison of a turbine blade before and after grinding on the Mägerle MFP 160-50 centre [8, 27]

4. Turbine blades grinding

The turbine vanes and rotor blades grinding have been implemented in last years by leading turbine and aircraft engine producers (e.g. Pratt & Whitney, General Electric Aircraft Engines, GE Power Systems, Rolls-Royce, Snecma Moteurs, VolvoAero, Avio), but the blade complex machining by one clamping operation occurred possible only after implementation the grinding machines with 5-axes CNC control.

The two main goals are connected with employing high-speed grinding technology, in which a higher peripheral grinding wheel speed advantage is used mainly: lowering products quality and increase of material removal rate and thus shortening the time of machining. It is possible to achieve a unit price cost considerable lowering in the result.
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The newest information confirmed carrying on hard works abroad in the aviation plants, machine tool factories, research centres and technical universities under development the technology, special control programs and machine tools with 5-6 axes CNC control for the high efficiency turbine blades abrasive machining by only one set-up operation.

By way of example Raysun Innovative Design Company, Rugby, UK, patented ‘Diatı’ process of the turbine blades grinding (patents: GB 2391188 published 04.02.2004; WO 2004011194 published 05.02.2004) with electroplated diamond grinding wheels. By grinding with cutting speed \( v_c = 50-150 \text{ m/s} \) the material removal rate per unit active grinding wheel width \( Q_w' = 50 \text{ mm}^3/\text{mm} \cdot \text{s} \) is obtained, when a coolant is delivered to the grinding zone from the inside of grinding wheel by channels under pressure of 30 bar and by the nozzles from the outside of grinding wheel under pressure of 80 bar.

The new idea of the turbine blade and vanes grinding in the grinding lines supported on PROFIMAT MC 607 grinding machines of Blohm, instead of grinding cells, implemented by aviation companies (e.g. Pratt & Whitney, USA; MTU Engines, Germany) is based on the following principles:

- the machine tools variety decrease – to achieve the synergy effect;
- the machine tools disposability increase – to decrease the machine tools structure complexity;
- reducing the uniform work stroke time on the machine tools in production line – to guarantee the flaw-line production capacity utilization.

Grinding makes possible reducing the set-up times and machining times (20%) by connecting the operations of flat and arc surfaces grinding, decreasing the occupied workshop’s floor-space (more than 50%), reducing the tooling costs of a machine tool (up to 72%), the abrasives (up to 35%), workshop auxiliaries (up to 80%).

<table>
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<th>Table 2. Technologies of high volume grinding [7-26]</th>
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<td>Process</td>
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| Grinding on a conventional machine | The nickel alloys grinding | \( Q_w' = 5\text{–}15 \text{ mm}^3/\text{mm} \cdot \text{s} \)  
\( v_s = 22 \text{ m/s} \); \( a_p = 3 \text{ mm} \) |
| HSCD method of Blohm  
High Speed Continuous Dressing | Grinding with conventional grinding wheels Ø400÷500 mm  
or cBN grinding wheels | \( Q_w' = 50\text{–}150 \text{ mm}^3/\text{mm} \cdot \text{s} \)  
\( v_s = 30\text{–}50 \text{ m/s} \); \( a_p = 3 \text{ mm} \)  
\( v_c = 170 \text{ m/s} \) (special option) |
| VIPER method of Rolls-Royce  
Vitreous Improved Performance Extreme Removal | The nickel alloys grinding with conventional grinding wheels Ø200 mm | \( Q_w' = 30\text{–}80 \text{ mm}^3/\text{mm} \cdot \text{s} \)  
\( v_s = 30\text{–}50 \text{ m/s} \) |
| ‘Diatı’ process of Raysun Innovative Design Company, Rugby, UK | Grinding with cBN EP grinding wheels | \( Q_w' = 50 \text{ mm}^3/\text{mm} \cdot \text{s} \)  
\( v_s = 50\text{–}150 \text{ m/s} \) |
| HEDG method of Holroyd – Edgetek  
High Efficiency Deep Grinding | Grinding with cBN EP grinding wheels Ø127÷254 mm | \( Q_w' = 50\text{–}2000 \text{ mm}^3/\text{mm} \cdot \text{s} \)  
\( v_s = 50\text{–}200 \text{ m/s} \); \( v_c = 0.05\text{–}55 \text{ mm/s} \)  
\( a_p = 0.05\text{–}1.5 \text{ mm} \) |

The HSCD method of BLOHM company enables obtaining material removal rates per unit active grinding wheel width \( Q_w' = 50\text{–}150 \text{ mm}^3/\text{mm} \cdot \text{s} \), when comparing with the nickel alloys grinding with cBN electroplated grinding wheels on a conventional grinding machine \( Q_w' = 5\text{–}15 \text{ mm}^3/\text{mm} \cdot \text{s} \) and grinding with VIPER method of Rolls-Royce company with the aluminium oxide grinding wheels with outside diameter of 200 mm \( Q_w' = 30\text{–}80 \text{ mm}^3/\text{mm} \cdot \text{s} \).
5. Grinding machines for the turbine blades grinding

To cope with requirements of a new idea of the turbine blades grinding (‘LEAN APPROACH’) with use of high-duty grinding HSCD (HSCD = High Speed Continuous Dressing or else designated with the other acronym: CD- or IPD-creep feed grinding) in the compact cells or the production grinding lines, the series of grinding machines BLOHM PROFIMAT type MC (Fig. 4a – with a stationary table) and RT (Fig. 4b – with a rotary indexable table) have been designed. The series of MC grinding machines enclose MC 407, MC 607, MC 610, MC 607 VG types [20]. The competitive grinding / machining 5-axes centre of Mägerle type MFP-TC is shown in Fig. 4c.

The MC 607 production grinding machine is very compact and takes place of 3,750 x 2,000 (width) mm. The main features of this grinding machine are: a large surface of a table (700 x 600 mm), main spindle in standard version with electric motor of power 45 kW with stepless drive for the wheel rotational speed up to 6,000 min⁻¹ or in special option with electric motor of power 60 kW, n = 8,000 min⁻¹, which enables achieving the grinding wheel peripheral speed v = 170 m/s. There is a possibility of using the conventional grinding wheels with outside diameter 400, 450, 500 mm with patented by BLOHM (patent numbers: DE19929466 A1 published 28.12.2000, EP 1063057 B1 published 17.11.2004) Continuous Dressing (CD) or In-Process Dressing (IPD), or else the grinding wheels (of smaller outside diameters) with cubic boron nitride (cBN) grains.

The diamond wheels dressing with the rotary diamond roller dressers during process of grinding allows a significant reducing the machining time and improves an active grinding wheel surface (AGWS) topography and increases a grinding wheel life. Preliminary shaping (truing) of AGWS decreases costs of continuous dressing with rotary diamond roller dressers during grinding.

The roller rail systems in all axes with the ground ball screws ensure an exact positioning and movements free of stick-slip effect. The work zone is completely enclosed and ensures environment from spreading of cooling liquid being delivered, under high pressure, by the directional delivery system numerically controlled, protected with patents (patents: DE 4129402 A1 published 11.03.1993, US 5313743 published 24.05.1994).

It should be stated that in the vertical grinding centres of BLOHM the workpiece dividing attachment, with CNC control, to the turbine blades a new clamping method during machining were applied (patents: DE 10062922 A1 published 20.06.2002, EP 1215012 A3 published 21.01.2004). The attachment enables three-dimensional complete machining of the workpieces (e.g. the turbine blades or turbine blades fragments required an angular or radial setting, etc.).

![Figure 4. a – the BLOHM PROFIMAT 607 MC grinding centre [27], b – the BLOHM PROFIMAT 607 RT grinding centre [27], c – the Mägerle MFP-TC 5-axes CD-grinding centre with automatic grinding wheel and tool changer [27]](image)

It is possible to equip the grinder optionally with a system of the grinding wheel automatic dynamic balancing, with a two-position table to simultaneous machining and unclamping – unloading / loading – clamping the workpiece, with the tool changing system of 50 positions for clamping the diamond roller dressers and the grinding wheels with hub flanges – allowing to their simple and fast changing.

![Figure 5 a – the EDGETEK 5-axes S.A.M. grinding centre [10, 27], b – a view of the work zone of S.A.M. grinding machine [10, 27]](image)
On EMO 2005 Trades [24] the BLOHM company presented a new one grinding machine BLOHM PROKOS equipped with linear motor drives, which is appropriate to the turbine blade grinding. It should be stated that in the vertical grinding centres of BLOHM the rotary indexing attachments for a new method of the turbine blade clamping when machining were used.

The typical grinding machines with 5-axes CNC control are grinding centres Holroyd-Edgetek type S.A.M. (with grinding cBN wheels Ø127÷254 mm) and S.A.M.-X.L. (with cBN grinding wheels Ø203÷305 mm); equipped with GE FANUC 16 Mi control system coupled with GE FANUC servo and grinding wheel spindle electric motors (Fig. 5a-b) [17-19, 26]. These grinding machines, among others, are used to turbine blades machining with employing HEDG grinding technology [17-19, 26]. Cycle times of HEDG grinding are 3÷4 times shorter when comparing to CFG grinding, because of up to ten times faster feed rates, and grinding wheel peripheral speed up to four times faster ($v_s = 200$ m/s) [17-19].

5.1. Features of the new technology HSCD of the turbine blades grinding

To recapitulate advantages of the new technology of the turbine blade grinding [7, 12, 23] it should be stated that HSCD BLOHM technology enables achieving the high capacities of grinding by application [23]:

- an active grinding wheel surface (AGWS) continuous dressing, what assures an allowance effective removing from the turbine blade blank surfaces;
- the pressure nozzles with CNC control in 2-axes, which are guiding a delivered cooling liquid strictly to a contact zone between a grinding wheel and a surface of the turbine blade being ground;
- a special attachment with a machined turbine blade two-side clamping, that enables a complete machining of a workpiece only in two set-up positions, instead of 8÷10 set-ups by conventional grinding;
- a storage magazine of grinding wheels with hub flanges – being replaced by a tool changer;
- the magazines of the coolant directing nozzles – being changed by the tool changer at the same time with changing the grinding wheels;
- shortening the turbine blades distance of transport, by arrangement PROFIMAT MC 607 grinders side by side in a grinding line, what enables the workpieces being machined, the manual changing by an operator;
- a workshop floor space decrease;
- improvement of the operating conditions and occupational safety by the noise emission reduction (i.e. an acoustic emission level) and the cooling liquid aerosols emission to the environment;
- a central system for delivery and filtration the cooling liquid for all grinding machines in the grinding line.

6. Abrasive belt grinding machines for the turbine blades grinding

The coated abrasive tools are used for finish grinding the turbine blade sculptured surfaces (Fig. 6b).

![Image](a) ![Image](b) ![Image](c)

Figure 6. The example of abrasive belt grinding machines and the turbine blades after finishing:

a – a typical robot cell of SURTECH in a booth and with pallet magazine [27];

b – the examples of turbine blades after airfoil finishing with use of SURTECH abrasive belt grinding machines [27],

c – abrasive belt mini grinder of SURTECH, with belt of widths from 6mm to 75 mm, for turbine blades and other difficult-to-machine parts [27].

The hand-held grinding machines, when workpiece is fixed, or the pedestal stationary belt grinding machines (Fig. 6c), when workpiece is guided by hand are usually employed to operations of the aerofoil finishing. The newest turbine blade grinding method with coated abrasives are the robot cells, where a workpiece to be ground is held and guided by a robot. The example of dedicated turbine blade finishing machine is the robot cell of SURTECH (Fig. 6a), which is equipped with the stationary abrasive belt grinding machine, the robot, the pallet magazine of the
turbine blades and the CNC control system. The 3D profile airfoil of a turbine blade or vane can be automatically ground and polished with application of such robotic system.

7. Abrasive brush deburring of the aircraft parts

The burrs arising on edges of the turbine blades, compressor blades, turbine blade rotor wheels and engine casings during machining and grinding operations could be removed directly on the machining centre [26] or on a separate specially designed automated or manually operated stands or at a robot cell (Fig. 7a-c).

The abrasive brushes, made of nylon round crimped, round straight or rectangular filaments impregnated with abrasive grain, are held in the tool magazine of the machining centre (e.g. Makino A55-5XR) along with the cutting tools and the grinding wheels. These brushes work as flexible files and deburr and blends edges, although they do not remove material rapidly like grinding wheels or coated abrasive products [26].

8. Unconventional machining the jet-engine parts

The application of the different unconventional technologies in the turbine blades and blisks machining (AWJM, AFM, ECM, EDM) are shown in Fig. 8. ECM is suitable for series production of medium size airfoils from Ti-blisks. Waterjet CNC Machines are employed to blisks and forged blade rough machining of airfoils. MTU Aero Engines published in [22] that ‘.a finished airfoil including radii on leading and trailing edge may be generated from a rough preform (made by ECM, milling or Water Jet Cutting) within 5 minutes’.

The lasers are other technology being employed in the jet engine components manufacturing. Laser turbine applications are: blade tip repair, nozzle guide vane repair, Z-notch welding.

9. Conclusions

A growing application of the different technologies of the abrasive machining is visible in manufacturing of the turbine components. The narrow tolerances of the workpieces and the surface roughness low values could be achieved by the way of the abrasive machining only.
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A great advance in technology of the turbine components manufacturing is visible. It should be stated after comparison of the technologies and machining / grinding centers of different manufacturers, which have been employed to the turbine blades abrasive machining, that BLOHM PROFINAT MC/RT grinding machines were designed specially to the newest technology of the aero-engine turbine rotor blades and turbine stator vanes high efficiency grinding. Those turbine blades and vanes are made of difficult to machine materials such as titanium and alloys on a base of aluminum, nickel and titanium. The HSCD BLOHM technology has been employed in the world since 2002 year, according to attainable information, while the VIPER process of Rolls-Royce had been implemented in 1999 [13, 16, 21].

The turbine blades abrasive machining is carried out in the grinding cells or in the grinding lines. A new strategy of the turbine blade grinding according to the modern technology HSCD BLOHM, which was accepted by producers from the aerospace industry (an aviation branch: e.g. Pratt & Whitney, East Hartford, USA; MTU Aero Engines, München, Germany) enables designing of a production flow-line in which some grinding machines BLOHM PROFINAT MC 607 and only one measuring machine are set together. These set of machines ensures a workpiece transport distance minimalization and reduction of the operators number necessary to operate the machines. Uniform production pace in that line is approx. 5 min. The machines setting in the grinding line makes possible a significant reduction (40÷50 %) of a product manufacturing costs per piece.

Technical parameters of PROFINAT MC 607 grinding machine and the users of BLOHM grinding machines opinions published in the foreign technical magazines indicate on a possibility of machining costs reducing of 40 % and machining times of 50 % in comparison with another technologies ensuring the machined surfaces high quality.

BLOHM PROFINAT MC grinding machines have been produced in different varieties for the last few years and the turbine blade producers have been satisfied with those machines, e.g. since 2002 year the Pratt & Whitney (USA) for manufacturing the turbine blades have exploited 21 grinders PROFINAT in 4 lines and to produce the turbine vanes have used 17 grinding machines in 4 lines [7]. The other manufacturer, MTU Engines, Germany, uses 3 PROFINAT MC 607 grinding machines in the grinding line to the turbine blades machining [23].

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    (Fig. 8c-d).

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