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HIGH SPEED MILLING OF TURBINE BLADES

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ABSTRACT

The efficiency of steam- and gasturbines is mainly influenced by the geometry and the surface roughness of the turbine blades. Therefore the profile contour of the blades must be machined as accurate as possible. High speed cutting (hsc) offers a lot of advantages for surface finishing of turbine blades. The paper describes the influence of different cutting parameters as well as the importance of tool geometry for the surface quality achievable by high speed milling. Specific requirements for machine tools for high speed milling will be discussed.

ADVANTAGES OF HIGH SPEED MILLING

High speed machining provides a range of advantages. Fig. 1 shows the essential characteristics of this technology [1].

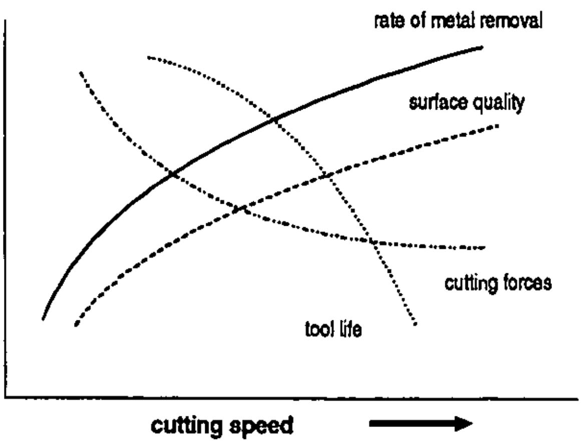

FIG. 1: CHARACTERISTICS OF HSC

These advantages can be used by producing blades for steam and compressor turbines. Beside higher time-cutting volume higher surface quality is achieved by a cutting speed which is raised by the factor 5 to 10. Since cutting forces decrease with increasing cutting speed thin blade profiles can be machined with better dimensional and contour accuracy. Additionally the heat flux into the workpiece decreases. So e.g. formation of tensile residual stress in the blade can be reduced.

Flow surfaces of turbine or compressor blades usually are free form surfaces. These convexly or concavely curved surfaces can either be machined by 3-axis milling using a ball end tool or by 5-axis milling using a cylindrical cutter. At 5-axis machining the direction of the milling cutter axis must be adjusted to the curvature of the surface by a tilting angle.

Free form surfaces can only be approximated by milling. A groove profile is produced, mainly determined by the pick feed. The remaining surface roughness usually requires a manual finishing work. Due to high cutting speeds and high feed rates hsc enables finishing of the surfaces with closely spaced cutter paths without a time disadvantage in comparison to conventional machining (fig. 2). Hence, it follows that the approximation of the desired contour by hsc is much better. Manual finishing work is not necessary.

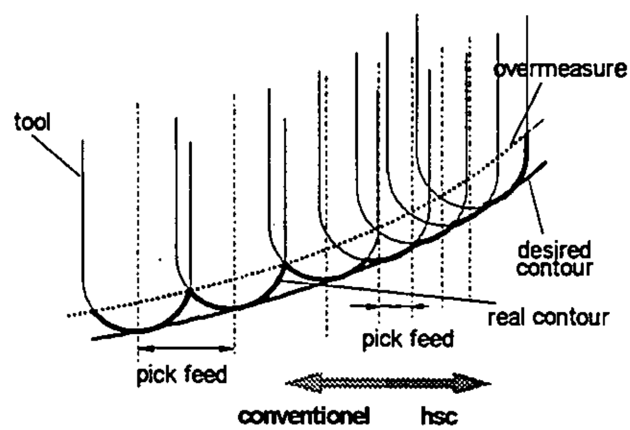

FIG. 2: INFLUENCE OF THE PICK FEED ON THE SURFACE ROUHGNESS

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With five axis milling cutter paths can be spaced more widely apart for a given peak to valley groove depth (fig. 3). Five axis milling additionally provides technological advantages [2]. With three axis milling in combination with a ball nosed cutter, the direction of the milling cutter axis cannot be changed and the effective cutting speed at the centre of the cutter is zero. These unfavourable cutting conditions are leading to poor workpiece surfaces and to heavy cutter wear. Using five-axis milling constant technological cutting conditions can be guarenteed.

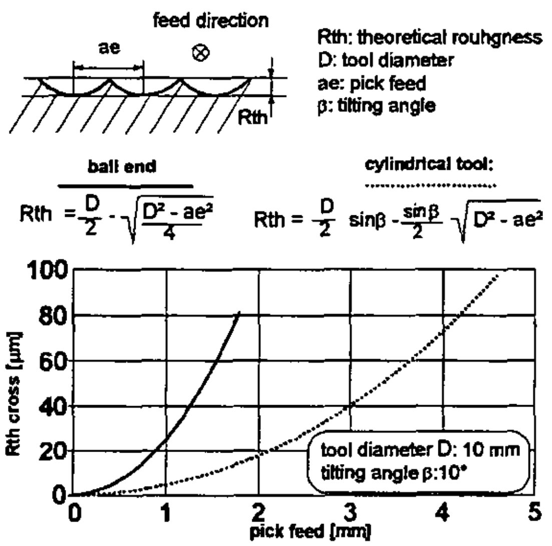


FIG. 3: INFLUENCE OF THE TOOL GEOMETRY ON THE SURFACE ROUGHNESS

MACHINING CONCEPT

Fig 4 shows the machining concept for five-axis milling of turbine blades.

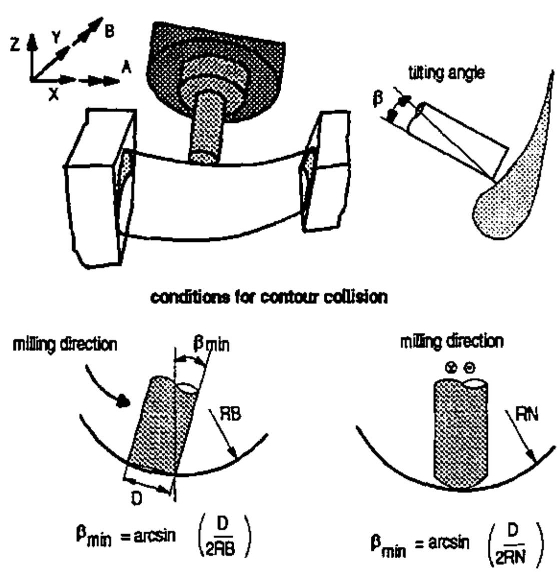


FIG. 4: MANUFACTURING OF BLADES BY 5-AXIS MILLING

The investigations at the Institute of Production Engineering and Machine Tools (PTW) were realized on a five-axis hsc machine with three linear and two rotary axis. In order to prevent contour damages by undercut, the milling cutter has to be set in feed direction. The mininum tilting angle is determined by the curvature of the surface in feed direction or crosswise (fig 4).

TECHNOLOGICAL INVESTIGATIONS

While high speed machining, the knowledge of optimum technological parameters is decisive for tool life and workpiece quality. Therefore basic technological investigations concerning the material X22CrMoV121 (DIN 17240, mat. nr 1.4962) have been done at the PTW. Cutting alloyed steel by high speed milling cutting speed is from 200 to 1,000 m/min.

The investigations covered machining steps semifinish (depth of cut 1.5 mm) and finish milling (depth of cut 0.5 mm). They were done on plane surfaces. An analysis of the blade-to-be-cut concerning collisions by undercut gave a necessary tilting angle of 20°. This angle was used during all tests.

TOOL'S EDGE RADIUS

When five-axis milling with a cylindrical cutter, the tool mainly cuts with the edge. This edge is mostly stressed by the the cutting process. The geometry of this edge radius therefore influences tool wear and especially surface roughness (fig. 5).

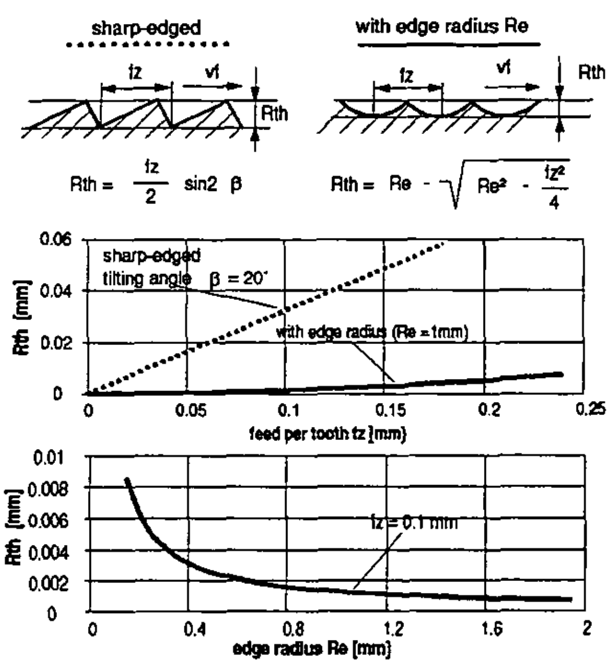
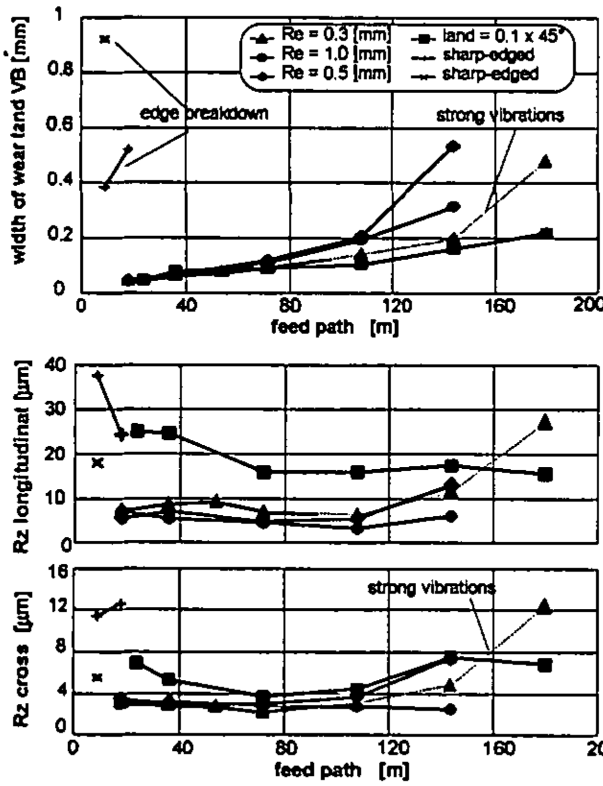


FIG. 5: INFLUENCE OF THE EDGE RADIUS OF A CYLINDRICAL MILLING CUTTER ON THE SURFACE ROUGHNESS IN FEED DIRECTION

At equal technological parameters surface roughness caused by sharp-edged tool is significantly higher as by a milling cutter with edge radius [3]. This connections are also approved by practical cutting tests (fig. 6). Using a cutting tool with an edge radius of 1 mm best surface quality in feed direction is obtained during complete tool life. Sharp-edged tools not only produced poor workpiece surface but also the cutting edges quickly broke out. Tools with edge radius of 0.3 mm showed longest tool life, but because of strong tool vibrations, the milling process was not longer stable from approximately 90 m on. The tool with a land showed a long tool life but a very bad surface. The results also confirme that an edge radius from 0.3 to 1 mm has no significant influence on the surface roughness perpendicular to the feed direction.



material:
X22CrMoV121
tool:
end mill: Ø 10 mm
number of flutes: 3
cutting material: K20/25-F TiN
overhang: 35 mm

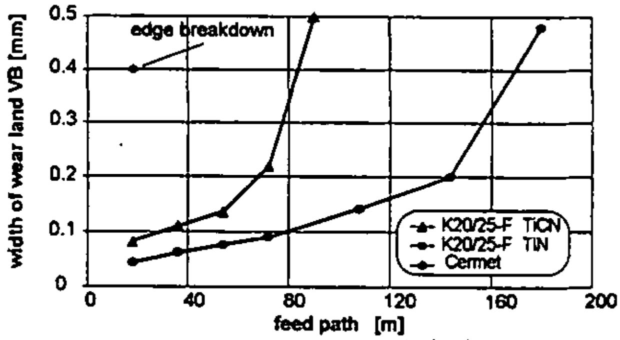
technology:
cutting speed: 400 m/min
feed: 0.1 mm
down milling
tilting angle: 20°
cutting depth: 1.5 mm
pick feed: 0.5 mm
without coolant

semifinishing

FIG 6: INFLUENCE OF THE EDGE RADIUS ON WEAR AND SURFACE ROUGHNESS

CUTTING MATERIALS

Fig. 7 shows the influence of the cutting material for the semifinishing process. Longest tool life and best surface quality were achieved with carbide K20/25-F with TiN coating. TiCN coating provides a very bad surface and a shorter tool life. Using cermet tools the high mechanical stress caused breakouts of the cutting edge and a total breakdown of the tool after a short feed path.



material:
X22CrMoV121

tool:
end mill: Ø 10 mm
edge radius: 0.3 mm
number of flutes: 3
overhang: 35 mm

technology:
cutting speed: 400 m/min
feed: 0.1 mm
down milling
tilting angle: 20°
cutting depth: 1.5 mm
pick feed: 0.5 mm
without coolant

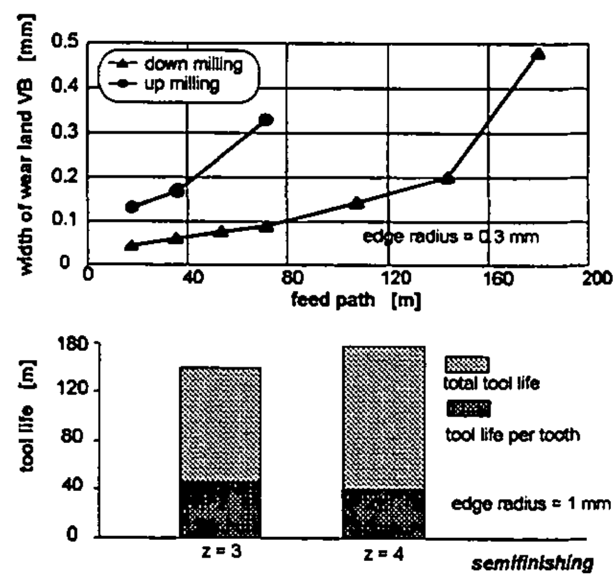
semifinishing

FIG. 7: INFLUENCE OF DIFFERENT CUTTING MATERIALS

NUMBER OF FLUTES AND MILLING STRATEGY

Fig. 8 shows a comparison of down and up milling. At up milling the tool encounters minimum chip thickness as it enters the workpiece and the friction conditions have a negative effect on tool life. The tool life is significantly smaller by up milling.

By raising the number of flutes from three to four a longer tool life is noticed, but the tool life per tooth of the milling cutter with four edges is shorter because of greater radial run-out of the flutes.



semifinishing

material:
X22CrMoV121

tool:
end mill: Ø 10 mm
cutting material: K20/25-F TiN
overhang: 35 mm

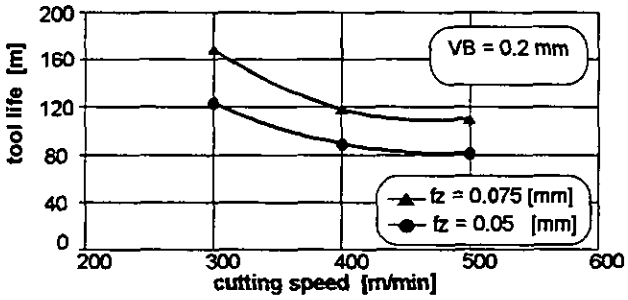
technology:
cutting speed: 400 m/min
feed: 0.1 mm
tilting angle: 20°
cutting depth: 1.5 mm
pick feed: 0.5 mm
without coolant

FIG. 8: INFLUENCE OF THE CUTTING STRATEGY AND THE NUMBER OF FLUTES

CUTTING SPEED AND FEED

Fig. 9 shows the influence of the cutting speed and the feed. Tool life decreases with increasing cutting speed, caused by the higher thermal stress [4]. Working with these small feed per tooth and this small depth of cut, the cutting process is within the rise per tooth limits so that the tool life decreases due to the raised frictional process. Additionally the small feed per tooth has a negative effect on the tool life caused by the higher number of cuts. The surface roughness longitudinal as well as perpendicular to the feed direction is within a range of 2 - 4 μm.

Because of the small chip thickness and -volumes by finishing, the chips are extremely heated up during the cutting process and are welded to the surface. Therefore spray cooling (emulsion) of the tool has to be used.



material:
X22CrMoV121
tool:
end mill: Ø 10
edge radius: 1 mm
number of teeth: 3
cutting material: K20/25-F TiN
overhang: 35 mm

technology:
down milling
tilting angle: 20°
cutting depth: 0.5 mm
pick feed: 0.5 mm
spray cooling
finishing

FIG. 9: INFLUENCE OF THE CUTTING SPEED AND THE FEED

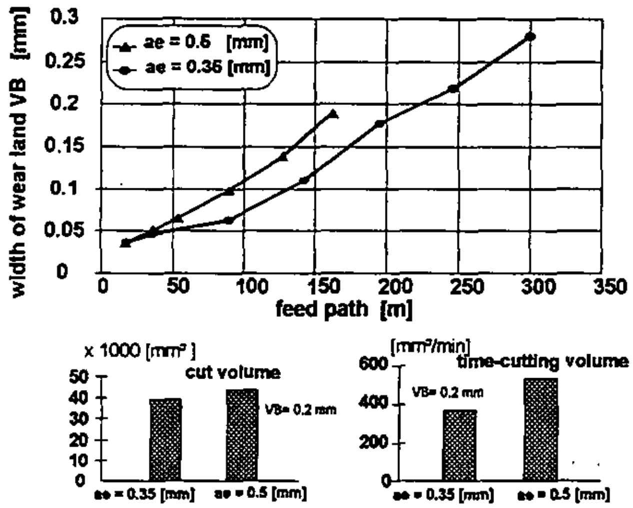
PICK FEED

With increasing pick feed shorted tool life will be obtained due to raised tool stress (fig. 10).

Decreasing pick feed, i.e. shorter heating up and longer cooling down phases leads to a raised tool life at high speed machining of steel. Choosing the pick feed and evaluating the economic efficiency the hourly machine rate and costs of tools have to be taken into account additionally .

REQUIREMENTS FOR THE MACHINE TOOL

By machining the free form surface of blades, the contour is approximated by linear interpolation. In order to minimize the inaccuracy, very short distances beetween the interpolation points are necessary. This causes big part programms with a lot of NC-blocks and very small feed steps.
Using optimum technology parameters for the machining, the machine tool needs high feed rates and also high acceleration.



material:
X22CrMoV121
tool:
end mill : Ø 10 mm
edge radius: 1 mm
number of teeth: 3
cutting material: K20/25-F TiN
overhang: 35 mm

technology:
cutting speed: 300 [m/min]
feed: 0.075 mm
down milling
tilting angle: 20°
cutting depth: 0.5 mm
spray cooling
finishing

FIG. 10: INFLUENCE OF THE PICK FEED

This is especially important for milling the blade's entering and outled edges, where little movements at the tool's end require very large copmpensation movements of the linear axes. Additionally, a jerk-free moving of the machines can only be guaranteed, if the data processing is fast enough to cope with the short distances between the points on the free form surface. If the data flow from the control system to the machine is interrupted the milling cutter "sputters" over the surface. Fig. 11 gives an overview of the important requirements for machine tools for hsc milling of turbine blades.

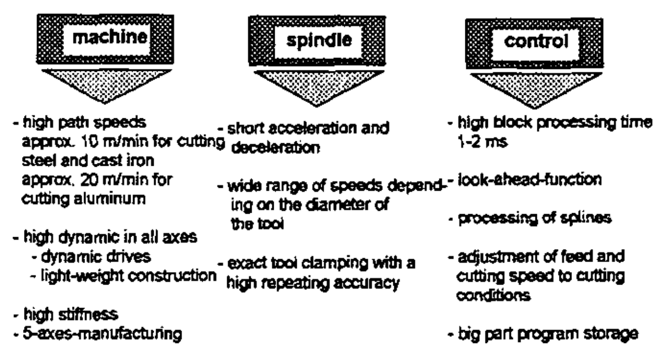


FIG. 11: IMPORTANT MACHINE TOOLS REQUIREMENTS FOR HSC MILLING OF TURBINE BLADES

RESULTS OF THE HSC MACHINING OF TURBINE BLADES

Fig. 12 shows a gas turbine profile milled by hsc. Because of the reduced cutting forces, the thin outled edge, which is normally difficult to machine, was milled with high accuracy.

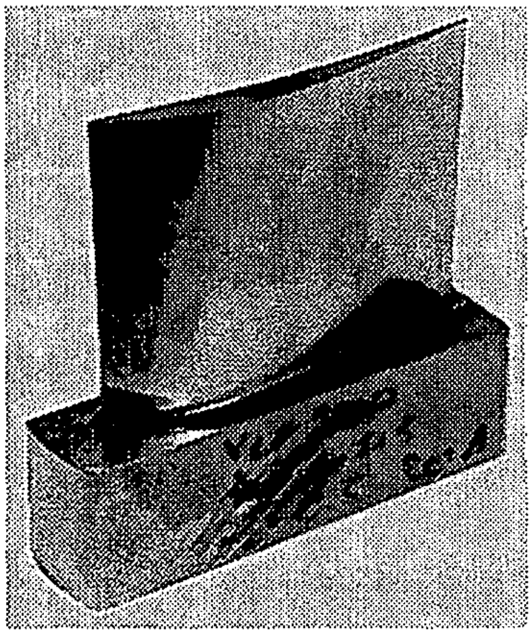


FIG 12: GAS TURBINE PROFILE MACHINED BY HSC

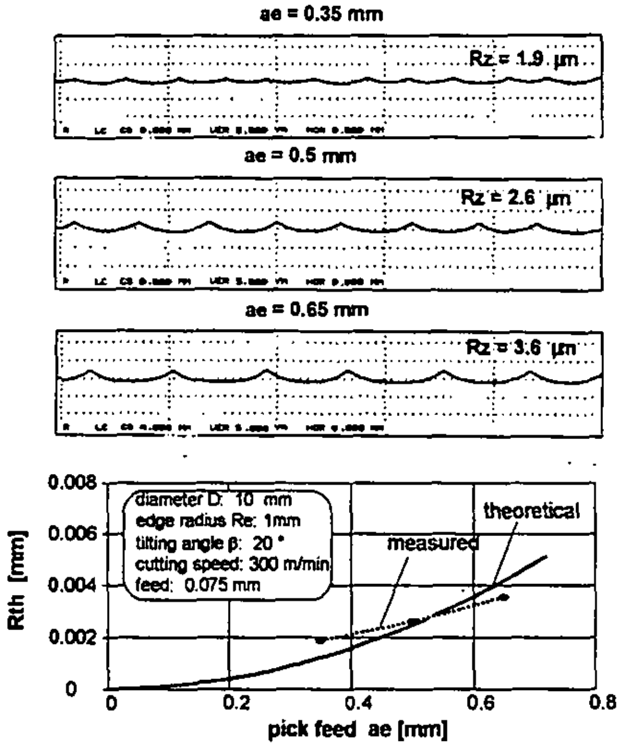


FIG. 13: SURFACE ROUGHNESS OF BLADES MACHINED BY HSC

As demonstrated in fig. 2 the surface roughness perpendicular to the feed direction is mainly influenced by the pick feed.

In fig. 13 measured surface profiles of milled blades are shown. The surface roughness of hsc milled steam and compressor blades was between 2 and 4 µm. Manuel finishing work was not necessary. The measured Rz-values do uearly match the calculated theoretical values. The results measured in the plain level can be directly transfered onto the curved profile.

It is more difficult to estimate the surface roughness in feed direction. The Rz values of the blades in this direction are higher compared to those of the plane sample. This is mainly caused by the wow and flutter of the machine drives. In contrast to the plain surface of the sample, all five axes are involved by the contour interpolation of the blades Additionally, the wear of the cutting edge and a possible radial run-out of the flutes directly can be observed on the surface profile in feed direction.

The biggest dimensional inaccuracies of the profile contour were between 0.02 and 0.04 mm. Any manual finishing work therefore becomes superflous.

SUMMARY

Concerning the finishing process of turbine blades high speed milling provides many advantages.

Manual finishing work of the surface is not necessary. The shape accuracy is clearly higher. Problematical geometry elements, like the thin outled can be machined without problems.

In order to guarantee an optimum operating result and a high process stability when using hsc, the technological parameters have to be optimized and hsc-adapted milling strategies have to be used.

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