Lecture Notes in Production Engineering

Berend Denkena *Editor*

New Production Technologies in Aerospace Industry

Proceedings of the 4th Machining Innovations Conference, Hannover, September 2013

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Preface

The aerospace industry is characterized by a high degree of research intensity and rapid developments. Due to this, aerospace industry has a high strategic importance in the development of innovative technologies.

"The aerospace industry is one of the most successful industries in Europe, but also one of the most challenging," says Hans-Joachim Peters, Chairman of the Machining Innovations Network e.V. and Head of Core Business Unit Part Production, Premium AEROTEC GmbH. "An important contribution to this leadership role is the innovative capacity of the suppliers with their production equipment and technology research," adds Peters. Despite the long timescales of individual projects due to the necessary approvals innovations are continuously implemented. Currently processes with a high resource efficiency but still good quality and increasing productivity, both in products and in production processes is sought after.

The demand for fuel and resource efficient aircrafts and flights is growing fast from a political as well as social viewpoint. This gives new relevance for the research of new materials and processes, which enable the production of safe and economic aircrafts. Innovative materials need adapted manufacturing processes and this in turn has an impact on planning and organization of factories, machine tools and manufacturing processes.

The Institute of Production Engineering and Machine Tools and the Machining Innovations Network e.V. present in 2013 the Machining Innovations Conference *New Production Technologies in Aerospace Industry*. A total of 26 experts from industry and science will report on two half-days in plenary and technical presentations of the latest innovations and trends. The topics of the different sessions are current trends in manufacturing and production technology as well as planning and organization. For the first time in the 13 year history of the conference, scientific presentations are presented with the latest research results on the key topics of the conference in an extra session. The articles belonging to this scientific session are presented within this issue of "Lecture Notes in Production Engineering".

Therefore, I'm looking forward to the conference as a whole and the scientific aspects in particular with presentations on current research, captivating presentations and lively discussions about the various aspects of *New Production Technologies in Aerospace Industry*.

Contents

High Performance Turning of High Temperature Alloys on Multi-Tasking Machine Tools

U. Karagüzel, U. Olgun, E. Uysal, E. Budak and M. Bakkal

Demands of aerospace industry for high performance alloys have been increasing due to their superior thermal and mechanical properties. These properties, on the other hand, decrease the machinability resulting in lower productivity. Conventional machining techniques can be insufficient to provide higher productivity for these cases. Special processes such as turn-milling and rotary turning can be remedy in increasing productivity in these applications. In order to test the performance of these processes, Mori Seiki NTX2000 mill-turn machining center is used. This machine includes nine axes with two chucks, a milling spindle and a turning turret. The milling spindle whose head moves along the X-, Y- and Z-axes and rotates around the B-axis is used to control the inclination angle in turn-milling and rotary turning tests.

Turn-Milling

Turn-milling (Fig. 1) is relatively a new cutting operation which combines two conventional manufacturing processes; turning and milling. This promising technology becomes an alternative to classical turning due to its advantages such as higher productivity and lower cutting temperatures which provide longer tool life. Intermittent characteristics of turn-milling helps maintaining lower cutting temperatures which make higher cutting speeds possible, produce smaller chips and reduce cutting forces. Parts with large diameters which cannot be turned at high speeds can be machined with increased productivity using milling tools at high rotational speeds. Furthermore, in turn-milling cutting forces applied on the part

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are reduced reducing deformations. Therefore, turn-milling had the potential to offer increased productivity and quality especially in machining of critical parts.

Tool wear

A cutting cycle in turn milling includes cutting and non-cutting periods which allows cutting edges to cool down reducing diffusive tool wear. In order to investigate this, tool wear experiments were conducted on a Mori Seiki NTX2000 multi-tasking machine. A 32 mm diameter Seco micro turbo 217.69-03 milling tool with three cutting teeth was used in the experiments. The inserts were F40 M grade which is recommended for machining super alloys. The work piece materials were Inconel 718 and Waspaloy which are commonly used in gas turbine hot sections. The cutting conditions used in experiments are as follows: 45 m/min cutting speed, 0.4 mm/rev feed, 0.2 mm depth of cut and 8 mm feed per work piece revolution. Flank wear land on the cutting tools was measured at regular intervals using a microscope as shown in Figs. 1 and 2.

Figure 2 shows tool wear measurement results in machining of Inconel 718 with conventional turning using carbide tooling and turn-milling for different cooling conditions according to the tool life per cutting edge considering the fact that the milling tool has three cutting teeth. Overall, it can be concluded from these results that tool life is improved substantially in turn-milling. Turn-milling, even under dry cutting conditions, provides about 50 % times higher tool life compared to wet conventional turning. It can clearly be seen that coolant has a significant effect on tool wear in turn-milling. For a carbide tool life criteria of 0.4 mm of flank wear, turn-milling with coolant (either conventional or MQL, although MQL seems to yield better life at higher speeds) provides about 3–3.5 times higher life compared to conventional turning.

Waspaloy is another important material in aerospace engineering. Figure 3 shows comparison between conventional turning under dry conditions and turn-milling with wet and MQL cooling for the tool life per cutting edge as the cutting

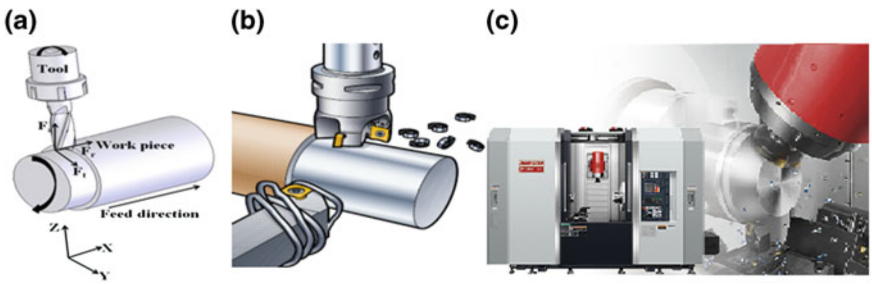

Fig. 1 **a** Turn-milling operation. **b** Chip disposal compared to conventional turning (Sandvik). **c** High performance turn-milling (Mori Seiki)

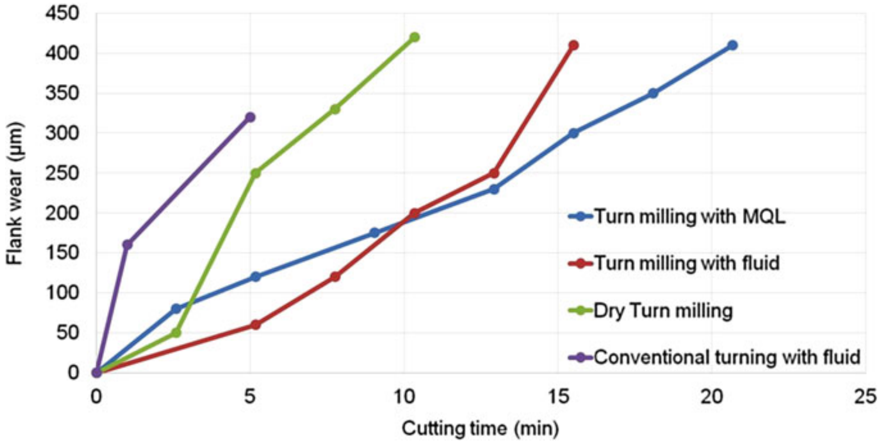

Fig. 2 Tool wear results of Inconel 718 for different cutting conditions

inserts immediately broke in dry turn-milling of waspalloy. One can see from Fig. 3 that tool life is increased substantially (up to 30 times) by turn-milling per cutting edge.

MRR (Material Removal Rate) Optimization

High MRR (Material Removal Rate) is possible in turn-milling but it may cause increased form errors in finishing as shown in Fig. 4. Turn-milling process does not produce an ideal circle. Since in turn-milling cutting tool and work piece rotate simultaneously, the resulting machined part cross section is a polygon as shown in

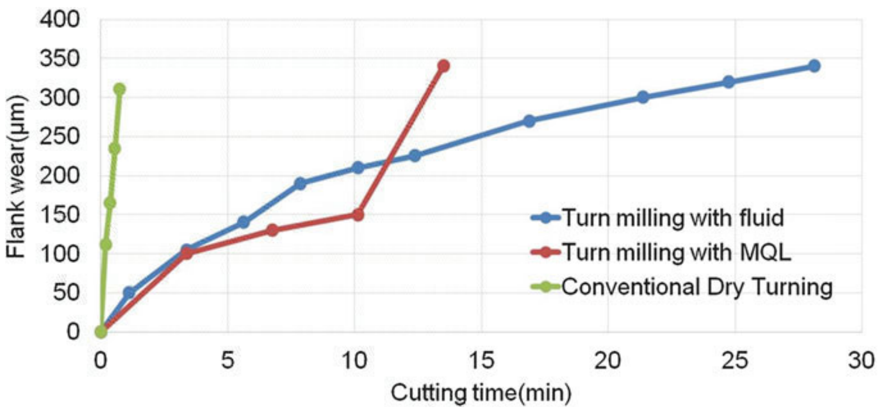

Fig. 3 Tool wear comparison between turn milling and conventional turning of Waspaloy

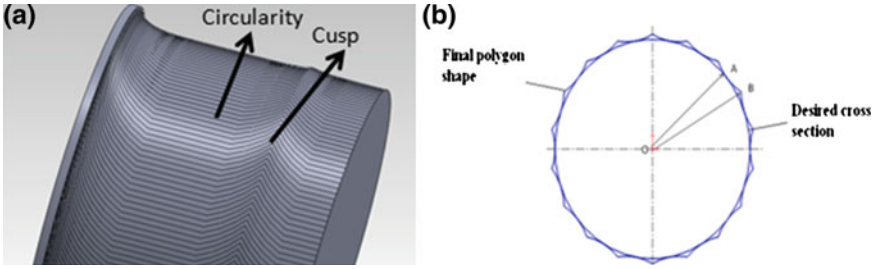

Fig. 4 **a** Form errors in turn-milling. **b** Circularity error (*cross section view*)

Fig. 4. If the feed per work piece revolution is increased for higher material removal rates, the cusp height shown in Fig. 4a is also increased.

Equations (1) and (2) explain the circularity error in turn-milling operations. In Fig. 4b, an ideal cross section and the one obtained in turn-milling can be seen. OB-OA in Eq. (2) describes the difference between desired and obtained cross sections.

$$\theta = \frac{2\pi}{z r_n} \tag{1}$$

$$OB - OA = (R_w - a_p)\left(\frac{1}{\cos\frac{\theta}{2}} - 1\right) \tag{2}$$

where z is the number of cutting teeth, r_n is the tool speed to work piece speed ratio, R_w is the work piece radius and a_p is the depth of cut. Figure 5 shows the effects of cutting conditions on the form error and tool life. As expected the tool life can be improved by decreasing the cutting speed at the cost of increased in circularity error. Figure 5b shows that MRR can be increased using higher feed per work piece revolution but again at the cost of reduced quality.

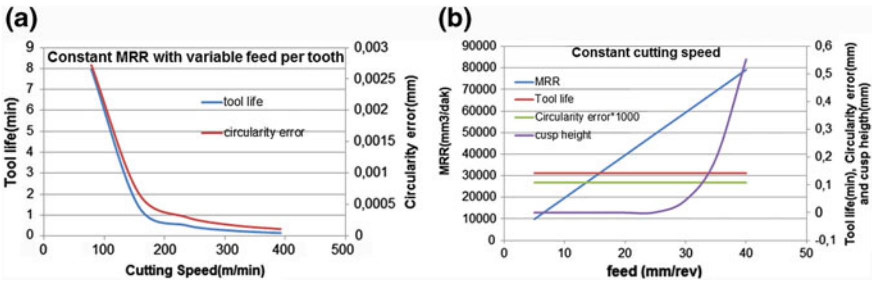

Fig. 5 Effect of cutting conditions on MRR and part quality in turn-milling

Rotary Turning

Rotary turning, which is a specialized turning process, can also be a remedy to improve the machinability and productivity of difficult-to-cut alloys. In this process, the round insert rotates continuously about its own axis during cutting. This tool rotation distributes the generated thermal energy to the whole cutting edge resulting lowered cutting temperatures and uniformly distributed flank wear on cutting edge. There are two types of rotary turning tools which are Self-Propelled Rotary Turning (SPRT) and Actively Driven Rotary Turning (ADRT) tools. In the former one, the tool is rotated by the action of the chip and cutting forces where the tool rotary speed depends on the workpiece geometry and the cutting speed. For the latter one, on the other hand, an external power source is used to rotate the insert. In this type, the tool speed and inclination can be adjusted independently. SPRT and ADRT processes can be seen in Fig. 6a, b, respectively. In this paper, only the ADRT tool performance for various difficult to machine alloys is presented.

The experimental set-up is shown in Fig. 6c. The tests were conducted under dry, flood coolant and MQL conditions with various tool speeds and tool inclination angles. The cutting tool used for ADRT is a carbide insert with multi-layer CVD coating of MT-Ti(C, N) + Al_2O_3 + TiN. It has 25 mm diameter with a chip breaker and 7° clearance angle.

The workpiece materials are Waspaloy, Ti6Al4 V and Inconel 718. 45 m/min cutting speed, 0.1 mm/rev feed and 0.2 mm depth of cut were used in the tests. Three different tool inclination angles (0°, 5°, 15°) and three different tool speeds (10 m/min, 20 m/min, 45 m/min) are tested.

Tool Wear

Tool wear results of ADRT process are presented in this section for various cutting conditions in comparison to conventional turning. In order to properly compare the lives of the stationary turning insert and the rotating one, normalization is

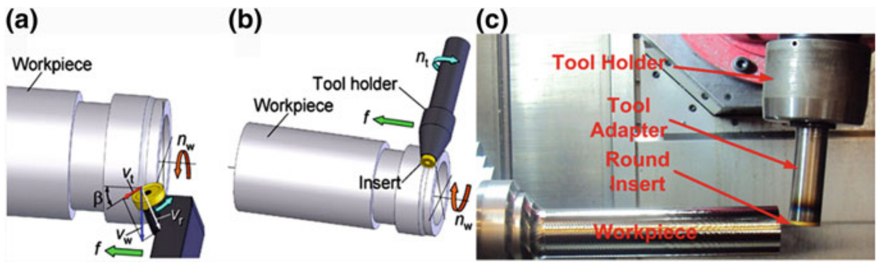

Fig. 6 Types of rotary turning (**a**) SPRT (**b**) ADRT (**c**) ADRT tool position on the mill-turn machine

necessary. This is due to the fact that when the rotating insert reaches the maximum allowable wear all around the cutting edge its useful life is finished and needs to be replaced whereas the stationary insert can be indexed and its unused portions can be used until the whole cutting edge is completely worn. The number of times the stationary insert can be used depends on its contact portion, and thus on the width of cut. In short, the measured tool life for stationary inserts must be multiplied by the number of indexing which is called normalization in this analysis. Figure 7a exhibits the *normalized* tool life test results for different rotary tool speeds on Waspaloy including conventional turning (Vt = 0) results. Cutting test results for Waspaloy indicate that increasing rotary tool speed after a certain range causes higher tool wear rate. At very low and high tool speeds, the tool life is the worst due to thermal effects. At low speeds the contact time between the tool and the workpiece increases whereas at higher speeds the required time for the tool to cool down is inadequate resulting in heat accumulation at the cutting edge as seen in Fig. 7a. For the best condition of rotary turning tool, tool life increases 43 % compared to conventional turning tool, i.e. for Vt = 0 m/min. On the other hand, increasing rotary tool inclination angle (shown in Fig. 6 as β) improves tool life as seen in Fig. 7b. Increasing inclination from 0° to 5° increases tool life 44 %, while a rise from 5° to 15° causes a further increase of up to 49 % in tool life.

Similar results are obtained for Ti6Al4 V cutting tests, i.e. as the tool inclination increases the tool wear rate decreases as shown in Fig. 8a. Figure 8b exhibits the effect of cooling condition on the tool life. Using coolant and MQL (Minimum Quantity Lubrication) improves tool life which can be attributed to reduced thermal shock on the cutting insert and more effective transportation of the cutting fluid to the cutting zone. Interestingly, for AISI 1050 steel cutting tests, dry condition gives the best result which may be explained by reduced thermal fatigue between high temperature (in cut) and low temperature (out of cut) regions.

Inconel 718 cutting tests also indicate that as the tool inclination angle increases, the tool life also increases as shown in Fig. 9a. Figure 9b shows the effect of coolant on the tool life where cutting fluid and MQL improves tool life 47 % and 12 % respectively, compared to dry cutting.

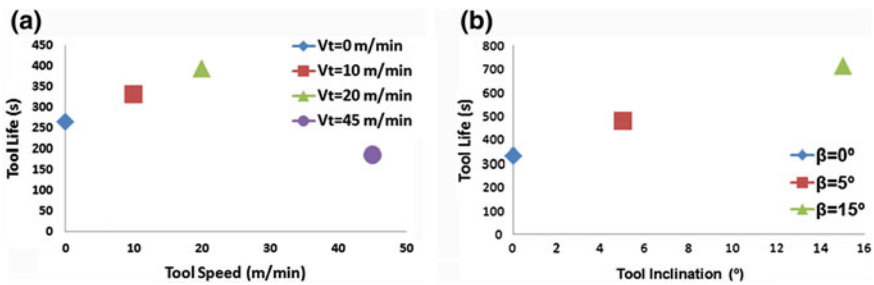

Fig. 7 The variation of tool life with **a** Tool speed. **b** Tool inclination angle for Vt = 10 m/min, cutting with coolant for Waspaloy

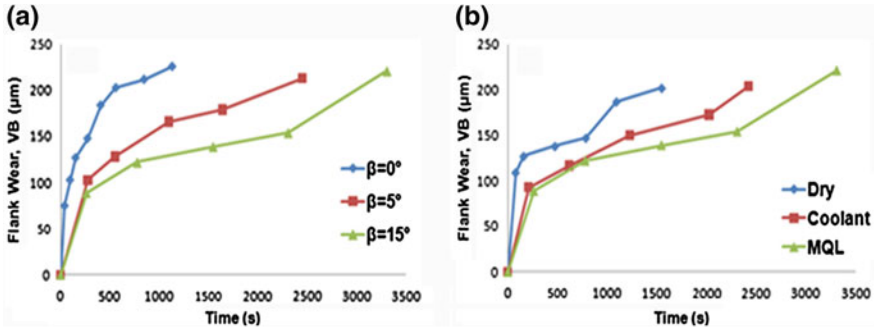

Fig. 8 Tool wear for Vt = 10 m/min **a** Different tool inclination angles for MQL cutting. **b** For different cooling conditions for $\beta = 15°$ for Ti6Al4 V

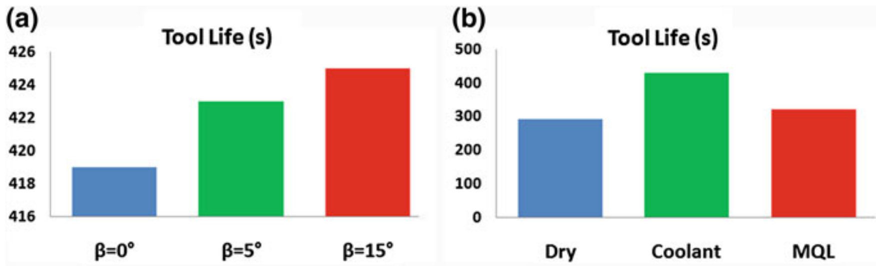

Fig. 9 Variation of tool life **a** With tool inclination angle for MQL, Vt = 10 m/min. **b** With cooling types for $\beta = 5°$, Vt = 20 m/min for Inconel 718

For Waspaloy cutting tests, cutting inserts for different cooling conditions, dry, coolant and MQL are examined under SEM as shown in Fig. 10. In all cases, flank wear is the dominant wear type where crater wear is not observed. High level of workpiece adhesion to the flank face is recognized, especially in dry cutting condition. These deposited materials re-enter the cutting zone due to tool rotation and triggers attrition of the tool material.

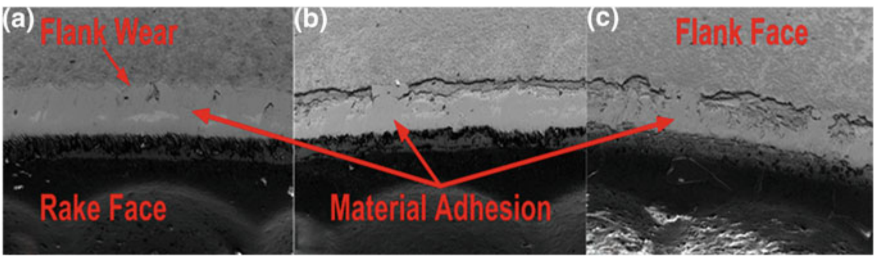

Fig. 10 SEM images of Waspaloy, Vt = 10 m/min, $\beta = 0°$ **a** Dry **b** Coolant **c** MQL conditions

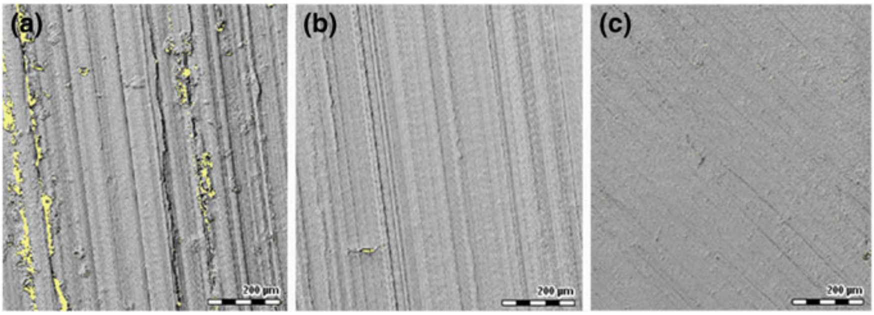

Fig. 11 Surface topography for different inclination angle and cooling conditions on AISI 1050 (**a**) 5°, MQL (**b**) 5°, Coolant (**c**) 0°, Coolant

Table 1 Surface roughness and circularity measurements for various tests

	5°, MQL	5°, Coolant	0°, Coolant
Roughness in feed directory	2.66 μm	1.22 μm	0.92 μm
Roughness in circumferential directory	1.33 μm	1.39 μm	1.44 μm
Circularity	35–43 μm	69–85 μm	29–30 μm

Surface Roughness and Circularity

Surface and form measurements were carried out in order to understand the effects of tool inclination and cooling conditions on the surface roughness and circularity of the workpiece, on test parts made out of AISI 1050 steel. As shown in Fig. 11, for 5° tool inclination, cutting traces on the surface can be seen at an angle to the feed direction due to tool spinning. 0° tool inclination provides better roughness results in the feed direction as shown in Table 1 where coolant improves roughness in the feed direction. MQL results in slightly better roughness in the circumferential direction compared to other cooling conditions. High circularity errors shown in Table 1 indicate that rotary turning process is suitable rough turning of difficult to cut alloys.

Conclusions

Multi-tasking machines offer opportunities to achieve higher machining productivity. Turn milling and rotary turning investigated in this study show that they can provide higher tooling performance in turning of high temperature alloys. Conventional turning is a continuous cutting process which produces high temperatures in cutting of special high temperature alloys. On the other hand, turn

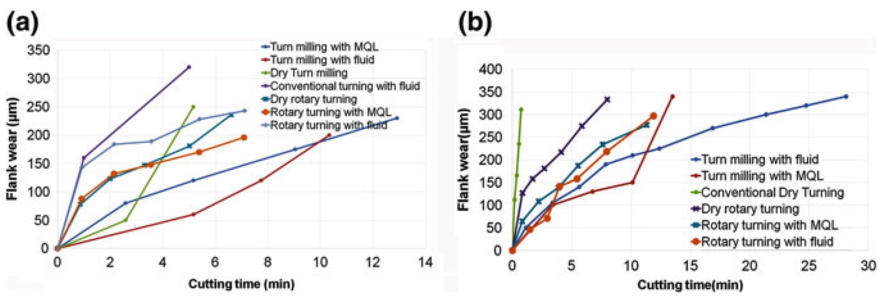

Fig. 12 Tool wear comparisons of turn milling, rotary turning and conventional turning for **a** Inconel 718 and **b** Waspalloy

milling and rotary turning are interrupted cutting operations which offer a chance to reduce cutting tool temperatures and improve tool life.

In this study, turn-milling and rotary turning operations are studied in terms of tool wear and machined part quality under different cutting and cooling conditions. As the summary of the tool wear measurements given in Fig. 12 shows rotary turning and turn milling provide much higher tool life (normalized for number of cutting edge and indexing) compared to conventional turning of Inconel 718 and Waspalloy.

Acknowledgments The support from Mori Seiki Corporation, Pratt and Whitney Canada and Turkish Scientific and Technological Research Foundation (Tubitak—Project 110M522) is appreciated by the authors.

Impact of Clamping Technology on Horizontal and Vertical Process Chain Performance

Roman Kalocsay, Thomas Bergs and Fritz Klocke

Abstract Clamping technology plays a major role in optimization of holistic process chains, determines auxiliary process times, enables process performance and affects workpiece quality. In this study we evaluate three different referencing strategies in horizontal process chains and discuss the effect of fixtures on workpiece dynamics. In order to achieve an optimal process chain performance an optimization of clamping solutions is crucial.

Keywords Clamping · Fixture design · Process chains · References · Damping

Introduction

To achieve robust and economic manufacturing, optimization is not limited to single process steps. A holistic approach must take into account the production process as a whole. It can be structured in two different scopes we call "vertical" and "horizontal process chain". In focus each manufacturing step can be divided into a sequence of tool path planning and machining operations, the "vertical process chain" (Fig. 1). Key factors regarding the optimization of a single operation in "vertical process chains" are machining parameters, tools, tool paths and fixture design amongst others. The "horizontal process chain" addresses the sequence of operations in a larger scope. Horizontal optimization deals with the efficient interconnection of process steps and involves logistics and harmonization of information transfer. Clamping technology can impact both directions of these process chains significantly to improve the overall production process.

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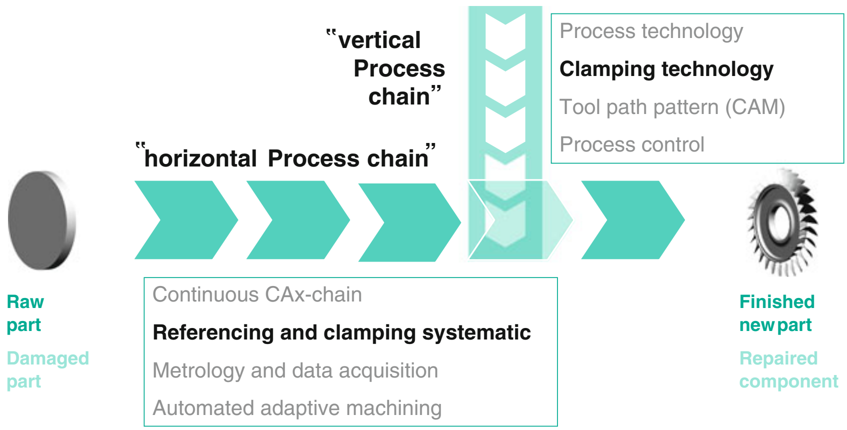

Fig. 1 Horizontal and vertical process chain

A first design theory on clamping devices was given by [1]. Willy [2] contributed a design method for fixtures in automated industry. In [3] active fixture design is outlined and in [4] a method for setup optimization is presented.

References and Positioning in Horizontal Process Chains

The performance of horizontal process chains mainly depends on positioning efforts. Optimization therefore requires dealing with references in clamping. Efficiency aims on data consistency, providing a fast way to establish defined relative positions of machine tools and workpieces in each process step. In the following three different approaches are presented (Fig. 2).

Clamping Device Based References

In this approach the workpiece is positioned at a predefined location in the machine tool. In this case movement is purely force driven using spring based, hydraulic or pneumatic kinematics pressing the workpiece onto rigid locators. To overcome jamming caused by friction before reaching the final stop position, the actors engage sequentially with subsequently increasing forces [5] or subsequently in a pulsewise manner maintaining a steady base load. By this means, a high repeat accuracy with usually less than 10 µm positioning tolerance can be achieved, depending on surface quality and friction deviation. In a second step the achieved workpiece position can be stabilized by attachment of additional supports.

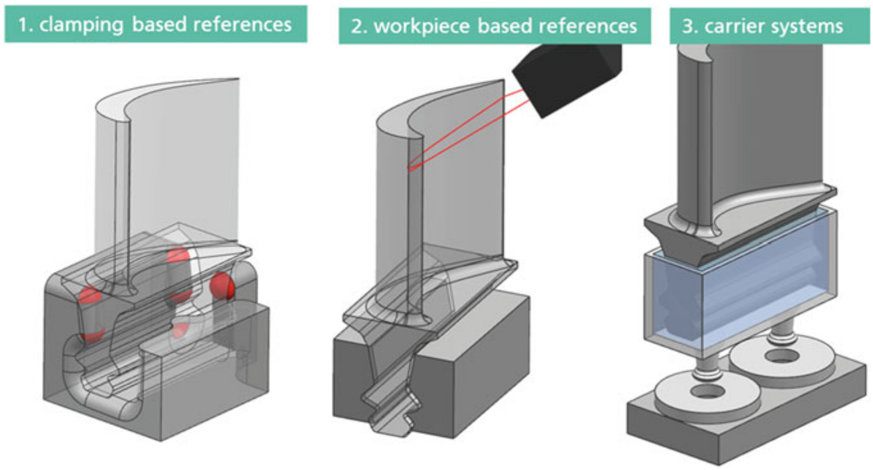

Fig. 2 Three referencing strategies; *left* clamping based referencing by clearly determined workpiece positioning; *middle* workpiece based referencing using data acquisition; *right* carrier system using cast in workpieces combined with a zero point system

In cast or forged workpieces large deviation of the form causes problems in clamping, especially due to uneven burrs at seams. Because of poor surface quality the classical force-driven positioning approach with rigid locators may lead to such large displacements of the center point that, even with reasonable oversize, geometry of the finished workpiece may exceed the boundary of material at machining position. Consequently, the high scrap rate often needs to be reduced by manual adaption efforts. This can be overcome by a centric positioning approach, which uses rigid kinematics (i.e. centric threads, knee levers or gears). It is crucial to keep the elasticity of the moving parts as low as possible. To enhance stiffness a two-stage approach can be followed: Centric positioning is achieved in the first step. In a second step positions of any moving elements are locked based on friction. Additional stability can be achieved by spring-loaded supports that are locked by friction in a third step. Given that kinematics are clearly determined in the positioning step, a repeat accuracy of <50 μm is achievable, depending on stiffness and bearing play of the kinematics.

In both approaches a high repeat accuracy can be achieved, whereas absolute accuracy of positioning might still be poor. High precision locators for exact positioning are prone to dirt and abrasives. Starting from the resulting natural clamped position of the workpiece and adjusting the machining by performing a calibration procedure offers a more robust and consistent approach. To determine the transfer matrix, the measured position of a reference workpiece relative to the coordinate system of the clamping device is compared with the CAD data being the basis for the CAM programming. The reference workpiece represents the average of the clamped parts, having reference geometry attached.