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Intelligent Fixtures for High Performance Machining

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Abstract

Fixtures are an essential element of the machining system, being part of the precision path and force flux between process and machine tool. Intelligent fixtures enable the identification of critical process conditions, a compensation of error influences and the minimization of defective parts. At first, this contribution presents a study in which the influence of the clamping setup and of the workpiece characteristics at various steps of the machining process is analyzed. Experimental and theoretical results regarding the dynamic process behavior reveal the relevance of these influences with respect to machining performance and workpiece quality. Secondly, the European research project INTEFIX is introduced. Representative approaches of intelligent fixtures, reducing workpiece vibrations and distortions, and improving workpiece alignment, are described and prototypes are shown. In a third part, two examples of intelligent fixtures are presented and discussed more in detail. The first example concerns a fixture for the identification and active mitigation of chatter in milling of thin walled workpieces. The second example is related to the compensation of workpiece distortions which occur in machining of large thin walled structural parts.

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Keywords: Fixtures; stability; distortions; alignment; sensors; actuators

1. Introduction

Fixtures and clamping devices are an essential part of machining systems for material removal processes. But their importance is often neglected or underestimated during the layout of manufacturing machinery and processing solutions. The relevance of fixtures regarding productivity, efficiency and quality is mostly not considered properly, e.g. with respect to the planning of production systems and related costs. Main tasks of fixtures and clamping systems are [1,2]:

- to define the location (position and orientation) of a clamped workpiece in the workspace of the machine tool
- to maintain this defined location even under the influence of static and dynamic mechanical and thermal loads
- and to guide these loads as an integral element of the machine structure inside the force flux

For automation purposes, the integration of an energy supply (hydraulics, pneumatics, electric power) and related interfaces is necessary. Furthermore, fixtures and clamping elements with integrated sensors for monitoring tasks are available [3-7]. Conventionally, fixtures should avoid any changes of the clamping point locations during the machining process. Flexible fixtures allow an adaptation of the clamping interfaces to the workpiece geometry [8-11]. Active fixtures enable an actuated movement of clamping points, e.g. for adaptation to distorting workpiece shapes [12,13], or to excite the workpiece in order to improve process conditions [14,15].

The accuracy, performance and reliability of a clamping scenario involving workpiece and fixture depends on the number, distribution and configuration of clamping devices and contact points including support pins or referencing elements. The layout of a fixture and the arrangement of clamps is a challenging task which can be accomplished by

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means of computer aided methods [16-18]. Since fixtures are part of the accuracy path of the machining system, their tolerances affect the quality of the processing result [19-21]. Fixture design can be supported by numerical calculation and simulation [22-24]. An essential aspect is the avoidance of workpiece deformations which can be caused by the clamping system itself [25]. In order to properly calculate and analyze the static and dynamic behavior of workpieces which are clamped in a fixture, an accurate modeling of the contact between the workpiece and the clamping element is important [26-28]. Testing of contact interfaces is necessary in order to parameterize and validate the calculation approaches [29-32]. Furthermore, the process-workpiece-fixture interaction has to be considered in assessing the performance of the fixture and to estimate the influence of a fixture layout on the machining process [33-35]. For compliant and thin-walled workpieces, the dynamic behavior of the machining process has to be analyzed carefully [36,37]. Modelling of the process-workpiece-fixture system allows the implementation of optimization strategies for attaining a suitable fixture layout [38-41]. A significant number of studies therefore aim in automated fixture configuration systems [42-46]. However, fixture design is dominated by the experience and knowledge of the designing engineer. Some approaches incorporate this knowledge into computer aided layout strategies [47,48]. Design methodologies for fixtures can be regarded as an ongoing topic, especially in view of intelligent fixtures [49].

In the following, a study is presented that reveals the relevance of the fixture layout with respect to the dynamic process-workpiece-fixture interaction. Afterwards, an overview of an ongoing European research project is given, which aims for the development of sensor and actuator integrated fixtures for thin walled and compliant workpieces. A final goal of this project is to provide design methods for such intelligent fixtures. Two examples for the simulation aided layout of intelligent fixtures are introduced in detail.

2. Relevance of fixtures

Since fixtures are located in the force flux of a machining system, their static, dynamic and also thermal behavior directly affects the quality and performance of the process. Regarding productivity and material removal rates, the vibration properties of the workpiece-fixture sub-system limit the range of stable process conditions. Consequently, fixtures are mostly over-dimensioned in order to provide sufficient stiffness and damping. However, this over-dimensioning leads to high costs and resource consumption.

For an improved fixture layout, basic analyses are necessary to gain a detailed knowledge of the dynamic behavior of the workpieces which are clamped in the fixtures. Furthermore, calculation and simulation approaches are necessary which allow an assessment of the performance of a designed fixture in a virtual environment during the layout procedure prior to the final hardware realization.

With the aim to reveal the influence of the fixture setup on the process stability in exemplary milling operations, a re-configurable test fixture was realized in cooperation with the company Roemheld (Fig. 1 and Fig. 2). The initial fixture setup incorporated three clamping points (equipped with supporting pins and swing clamps) and stoppers for referencing of the workpiece (Fig. 1a). This setup intentionally exhibits a certain dynamic weakness in less supported areas of the workpiece in order to enhance the visibility of vibration effects during the process. In further configurations, the locations and number of clamping points and additional supports vary (Fig. 1b).

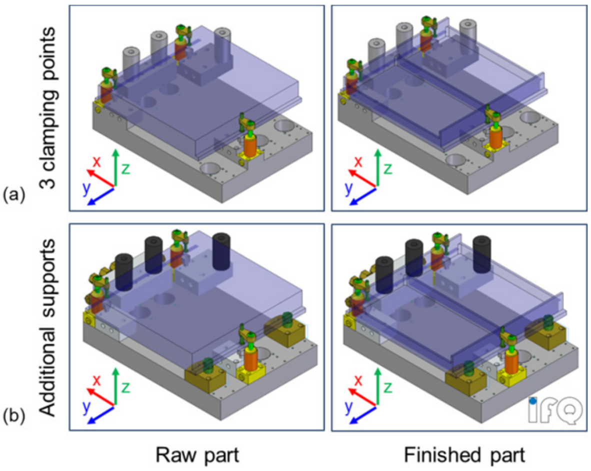

Fig. 1. Re-configurable test fixture for exemplary machining experiments; (a) initial fixture setup with three clamping points, (b) configuration with two additional hydraulic supports

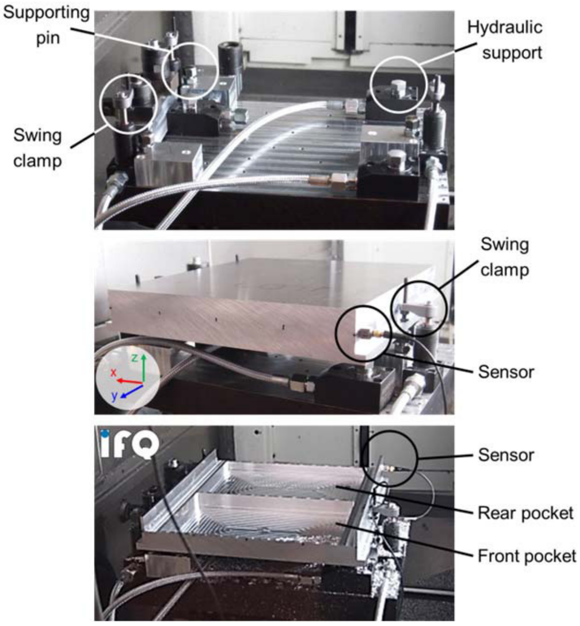

Fig. 2. Realized test fixture without and with clamped workpiece

The chosen milling test scenario consisted of a face milling of the top surface of the clamped raw material block and two pocket milling cycles with a circular strategy. Thus, the final workpiece has a ribbed and thin-walled structure. The workpiece material was Al7075. A coated 12 mm carbide tool with four cutting edges (z = 4) was used. The process parameters were n = 13,000min^{-1}, v_f = 4.2-4.5m/min, a_p = 3mm, a_e = 6-11mm. The workpiece vibrations were measured by a three-axis accelerometer as shown in Fig. 2.

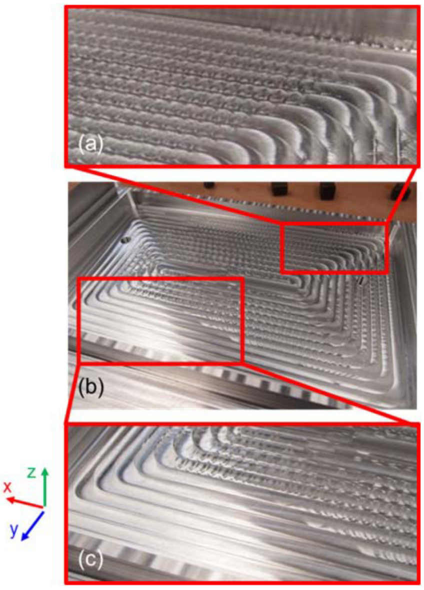

Fig. 3. Chatter marks in the rear pocket at a critical pocket depth; (a) chatter marks in upper right corner, (b) complete rear pocket, (c) smooth surface in left part of the rear pocket

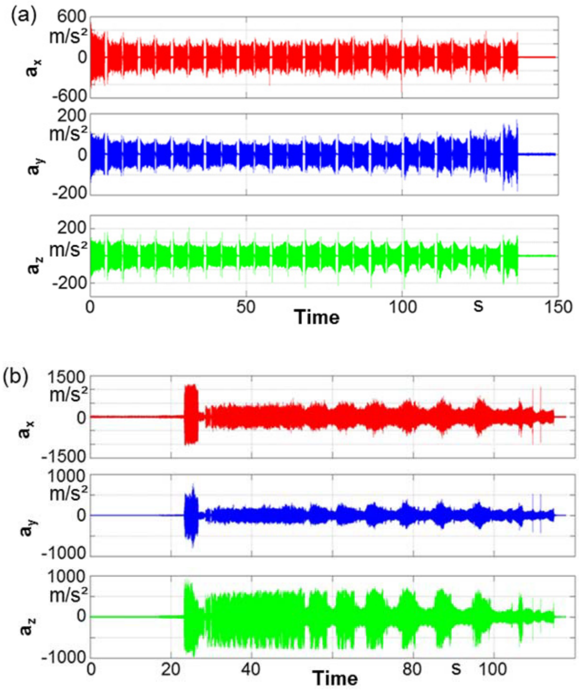

Fig. 4. Workpiece vibrations during milling of the testpart; (a) workpiece vibrations during face milling, (b) workpiece vibrations during milling of rear pocket

Even with the weak initial clamping setup, stable process conditions prevailed for the face milling and front pocket milling process steps. When milling the rear pocket, unstable conditions arose starting from a pocket depth of 15mm (equivalent to a pocket floor thickness of 13mm) (Fig. 3). Chatter occurred merely in the upper right corner of the pocket (Fig. 3a), where the fixture possesses the weakest workpiece support. During the circular milling operation, the cutting process changed recurrently between stable and unstable behavior. The left part of the pocket shows a smooth surface (Fig. 3c). The measured workpiece vibrations confirm this change between stable and unstable conditions (Fig. 4). Fig. 4a shows the measured workpiece vibrations during the face milling step. Besides some points of time in which no contact between tool and workpiece is given (overrun at end of linear path), uniform and relatively small vibration amplitudes occur. Fig. 4b depicts the workpiece vibrations during milling the rear pocket. Much higher and changing amplitudes can be observed.

In order to reproduce the experimental results and to allow a simulation based investigation of the workpiece and fixture behavior, Finite Element (FE) analysis of the fixture dynamics and process simulations for chatter identification were conducted (Fig. 5 and Fig. 6).

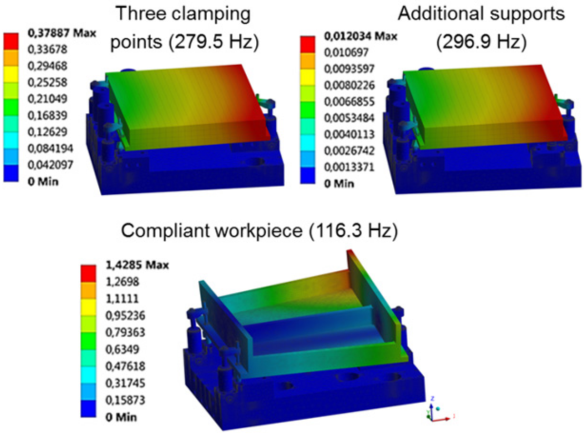

Fig. 5. FE analysis of different workpiece-fixture setups

Table 1. Measured and calculated modes of fixture with clamped raw part

Mode	Fixture with 3 clamps (measured)		3 clamps + 2 supports (measured)		3 clamps (FE analysis)	3 clamps + 2 supports (FE analysis)
	Frequency [Hz]	**Damping [%]**	**Frequency [Hz]**	**Damping [%]**	**Frequency [Hz]**	**Frequency [Hz]**
1	168	2.85	180	2.72	279	297
2	214	3.29	219	3.30	396	416
3	276	2.27	322	1.01	470	490

In Fig. 5 first natural modes of different workpiece and fixture setups are presented. Table 1 compares the calculated results with measurements. The FE analysis overestimates the natural frequencies due to simplifications in the contact modelling. However, the influence of the additional supports is well reproduced. The calculation results also show that the workpiece dynamics become dominant with a certain material removal state and the total vibration behavior changes drastically. The modal parameter values of the workpiece-fixture system can be used in process simulations [50] in order to identify unstable process conditions (Fig. 6).

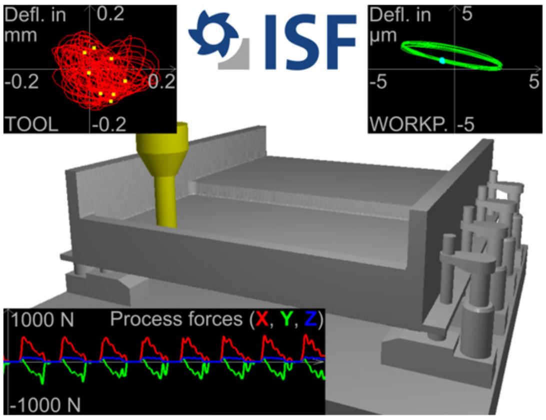

Fig. 6. Geometrical physically based process simulation incorporating the behavior of the workpiece-fixture system

This study confirms that the whole process-workpiece-fixture system has to be considered in fixture design, layout and optimization. The workpiece dynamics can alter considerably during the process and the system behavior can change drastically.

3. Intelligent fixtures

In the European research project INTEFIX ("Intelligent Fixtures for the manufacturing of low rigidity components"), sensor and actuator integrated fixtures are developed to overcome the challenges of vibrations, deformations and positioning in machining of thin-walled and large workpieces in the aerospace and transport sector:

- Vibrations occur in machining operations of thin-walled parts due to the dynamic compliance of the workpiece and the excitation by the process.
- Deformations of thin-walled workpieces result from gravitational and clamping forces, process loads and residual stresses which appear due to the machining process.
- Positioning of large parts inside the workspace of machine tools includes the referencing of difficult to handle components, which often do not possess reference points, and the adjustment of the position and orientation of the workpieces in order to meet accuracy requirements.

The integration of sensors and actuators leads to closed loop control architectures which enable an autonomous functionality of the fixture or an interaction and operation with the machine tool control. In the following, some examples of prototypes which are developed within the INTEFIX project are introduced. By this, an overview of the approaches to tackle the above mentioned challenges is given.

A first example for the avoidance of critical vibrations in turning of airplane turbine casings is shown in Fig. 7. The approach includes the variation of the location and force of the clamping pins in order to control the transient workpiece deformation which is caused by the process forces (Fig. 8). Additionally, MICA200M vibration absorbers are integrated in order to dissipate vibration energy and to damp the part.

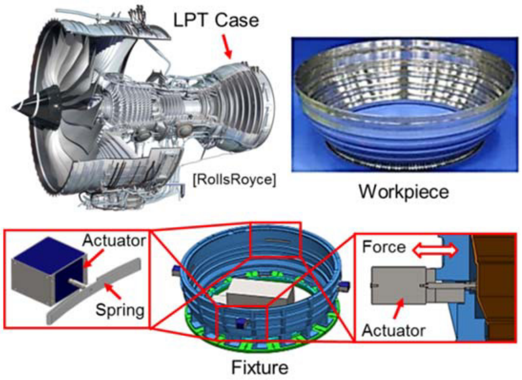

Fig. 7. Intelligent fixture to avoid workpiece vibrations in turning [Tekniker, Cedrat, Alava, ITP, INVENT, CompoTech, Wölfel]

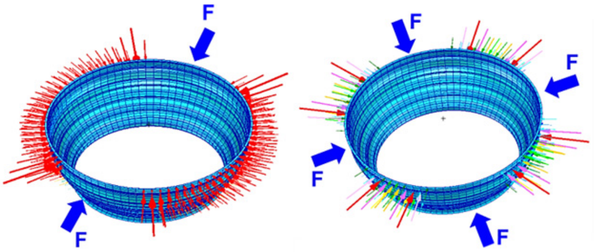

Fig. 8. Applied forces and apparent stiffness at thin-walled workpiece [Tekniker]

Examples for the avoidance and compensation of workpiece deformations are shown in Fig. 9. Fig. 9a depicts an approach in which the distributed clamping pistons are position controlled and can be moved in order to compensate workpiece distortions due to clamping forces and decreasing structural stiffness of the workpiece during machining.

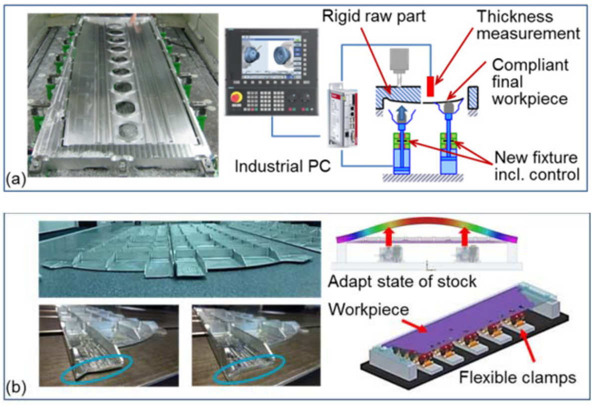

Fig. 9. Intelligent fixtures for deformation compensation; (a) compensation of forces, (b) compensation of residual stresses [RCMT, TYC, Roemheld, Kale Havacilik, Matzat, Ideko]

In Fig. 9b the compensation of distortions caused by residual stresses is shown. In this approach the distortions are estimated by model calculations and compensated by an active modification of the stock for machining. Adaptive hydraulic clamps hold the part at its ribs.

In Fig. 10 an example for leveling of large parts by controlled support points is shown. In addition to the position correction, self-adjusting clamping units for supplementary support points are integrated to reduce vibrations and to pre-deform the workpiece. Fig. 11 depicts a fixture which measures the workpiece contour and interacts with the machine tool control for tool path correction. A laser sensor is handled by a 3-axes sub-system inside the fixture. The supporting pins are elevated with a reduced air pressure until contacting the workpiece. In this moment the pins are blocked in that position. Then the vacuum pads fix the workpiece. An increase of damping by a factor of 10 using the additional vacuum cups could be achieved in experiments.

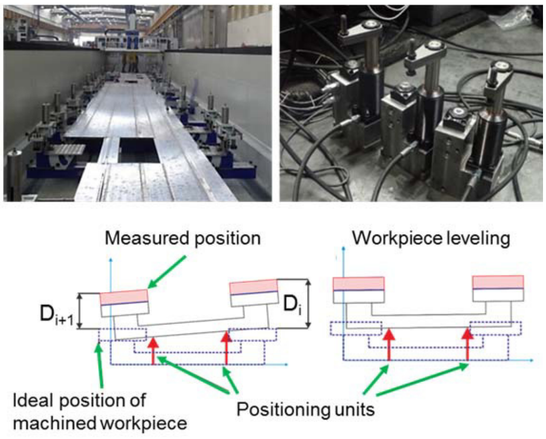

Fig. 10. Intelligent fixture for automatic leveling of large train parts [TYC, RCMT, Roemheld, Wölfel]

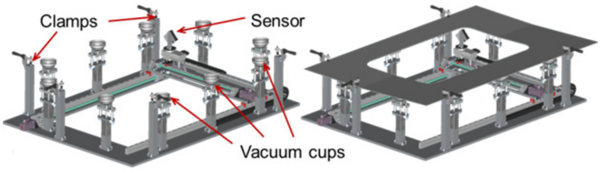

Fig. 11. Intelligent fixture with integrated sensor [Bereiker, Tekniker, Mesurex, Zayer]

(Not all the developments and prototypes of the INTEFIX project can be introduced here. More information is available at www.intefix.eu.)

4. Fixtures for the reduction of workpiece vibrations

In machining of impeller blades, chatter vibrations occur due to the low stiffness of the thin-walled structures (Fig. 12). This leads to an inacceptable surface quality and increased tool wear. Therefore, conventionally the process parameter values are reduced in order to avoid such critical conditions.

Within the INTEFIX project, approaches are followed in which counter excitations are introduced into the workpiece by actuated active fixtures. The aim of counter excitations is to disturb the regenerative chatter effect and thus to stabilize the milling system dynamics. The workpiece excitation can be realized in three different ways: in (a) two translational degrees of freedom (DoF), (b) one rotational DoF, or (c) two tilting DoF (Fig. 13). Since solution (b) works with only one actuator, it constitutes the least complex and most cost-effective approach.

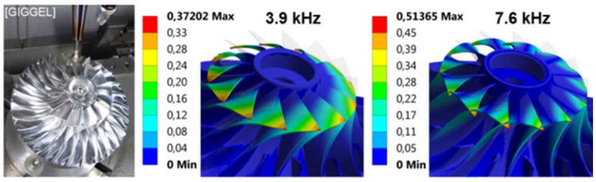

Fig. 12. Workpiece vibrations of the blades of an exemplary impeller (Al7075, D = 200mm, h = 65mm)

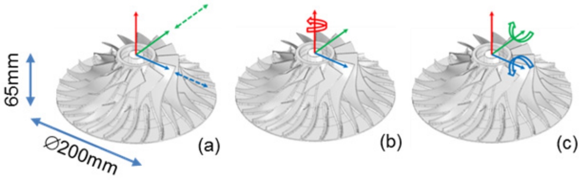

Fig. 13. Principle ways of introducing counter excitations; (a) 2-DoF translational, (b) 1-DoF rotational, (c) 2-DoF tilting

For analyzing solution (b), an active chuck with vibration sensors, a single piezo actuator and flexure hinges was developed (Fig. 14). Also, a simplified 1-DoF translational test rig was built, which allows investigations on vibration measuring and counter excitation strategies (Fig. 15).

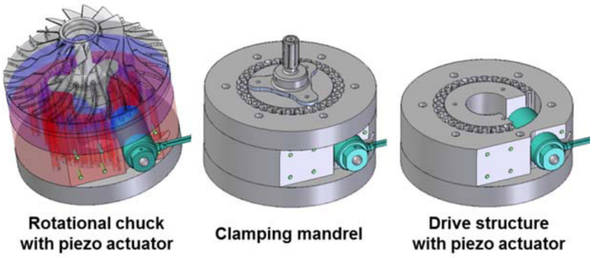

Fig. 14. Rotational active chuck and 1-DoF translational test rig

In basic milling experiments, the 1-DoF test fixture carries a simple straight plate. For measuring workpiece vibrations, a sensory CFRP (carbon fiber reinforced plastic) pad (provided by INVENT) is mounted between the workpiece and the moving table of the fixture. The workpiece vibrations are also measured by laser triangulation sensors which can be connected to the test rig. Experiments show that a less wavy machined workpiece surface can be achieved by the application of counter excitations [51]. Roughness values of Ra = 3.35 µm are reduced to Ra = 0.68 µm. The process stability of the milling operation of the thin plate was also analyzed using process simulations [51,52] (Fig. 16). Regions of the blade, where stable and unstable process conditions occur, can be identified (Fig. 17).

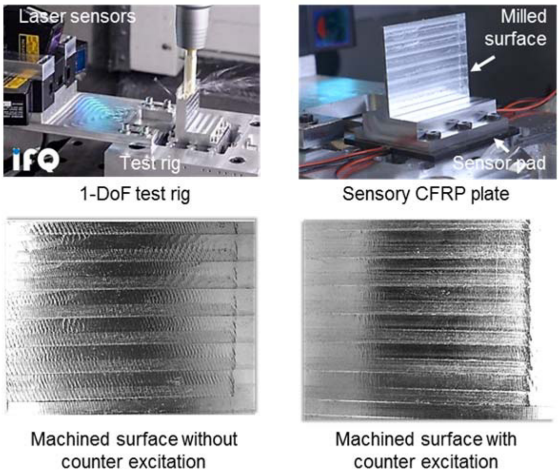

Fig. 15. Milling tests, integrated sensors, machining results

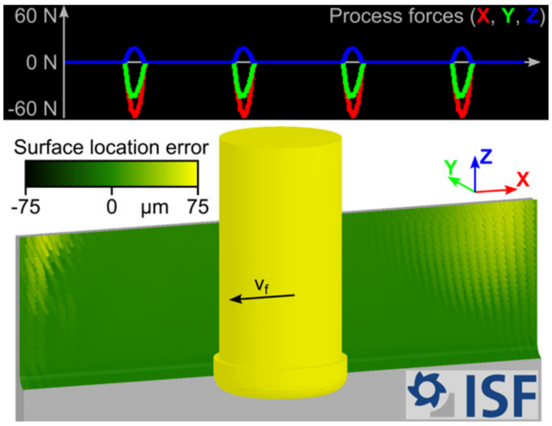

Fig. 16. Process simulation results for milling [51]

The simulation also allows the prediction of surface properties in unstable (1) and stable (2) regions (Fig. 17). Furthermore, the stabilizing effect of counter excitation with a frequency of 1.5 kHz can be approved (3).

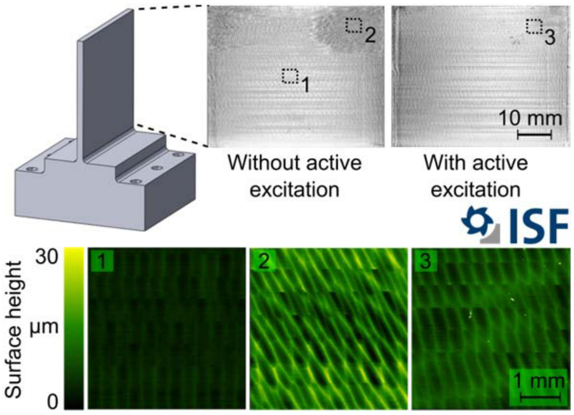

Fig. 17. Simulated workpiece surface regions [51]

5. Fixtures for the reduction of workpiece distortions

In order to overcome the problem of workpiece distortions due to residual stresses which occur in milling of thin-walled aluminum parts, special fixture frames have been developed which allow machining from both sides of the part (Fig. 18, Fig. 19). The workpiece is held inside of these frames by distributed PosiFlex floating clamps (by Roemheld) which enable an adaptation of each clamping point location to the distorted shape of the part. The strategy to minimize distortions of the workpiece after processing is based on a frequent relaxation of the workpiece inside the fixture at intermediate steps of the overall process. For this relaxation, an actuated movement of the floating clamps is provided by hydraulic pistons (Fig. 19). By means of strain gauges which are mounted at the actuation mechanism, the forces which act at each clamping point can be measured and utilized for control purposes. With the aim to improve damping of the fixture, CFRP frame elements (by INVENT) were tested successfully (Fig. 18c).

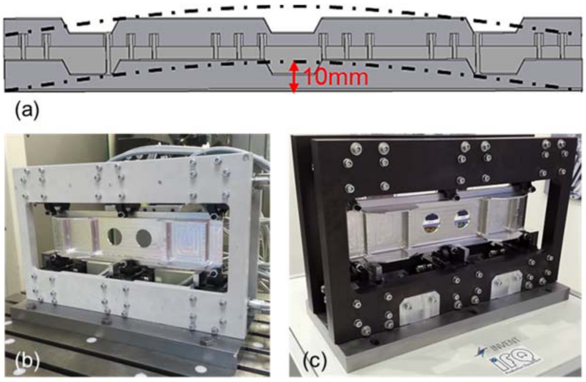

Fig. 18. Fixture frames for thin-walled aerospace structural parts; (a) distortion profile, (b) steel fixture frame with PosiFlex clamp, (c) CFRP fixture frame with PosiFlex clamp [INVENT]

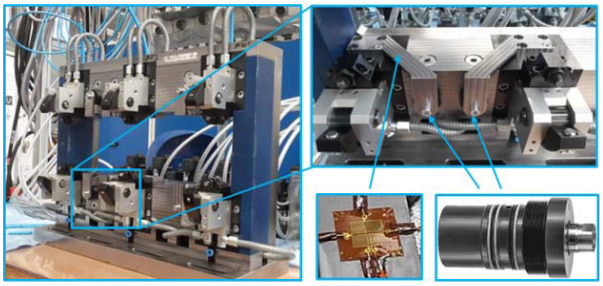

Fig. 19. Integration of sensors and actuators in fixture frame with PosiFlex clamping claws

The dynamic behavior of the fixture frames was investigated by FE simulations and experimental modal analysis with and without a clamped workpiece and for different states of the workpiece at intermediate processing steps. The measured natural frequencies for the fixture in Fig. 19 are summarized in Table 2. The obtained dynamic characteristics of the fixture can be used as input parameter values for process simulations and stability analysis (Fig. 20).

Table 2. Natural frequencies of a selected fixture frame

Mode	**Natural frequency [Hz] at different processing steps (initial, 1, 2, 3, final) and without workpiece (wwp)**					
	initial	**1**	**2**	**3**	**final**	**wwp**
1	138	145	141	148	146	130
2	296	298	294	300	300	263
3	619	600	603	615	619	345
4	777	760	745	714	715	500
5	973	966	971	984	984	587
6	1288	1278	1277	1304	1350	899
7	1514	1557	1553	1549	1448	1413
8	1859	1786	1783	1826	1827	1833

The stability charts for two different workpiece states are exemplarily shown. The stability limits were calculated using frequency response functions (FRF) which were measured at the tool center point (blue limit) and at the workpiece (red limit). Assuming that eigenmodes of the machine tool are not dominant for the analyzed process, the FRF determined at the tool represents the dynamic behavior of the tool, the tool holder, and the spindle; the FRF at the workpiece the behavior of the fixture-workpiece system. The comparison of the stability shows that the stability of the analyzed process is not limited by the dynamic behavior of the fixture but by the dynamics of the tool-tool holder-spindle system.

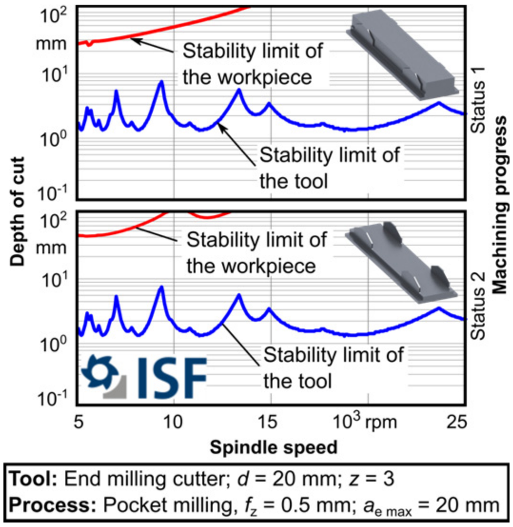

Fig. 20. Simulated stability diagrams for different process scenarios [53]

6. Summary and conclusion

In this paper the current state of intelligent fixture design is reviewed. The relevance of fixtures with respect to the performance and accuracy of machining processes is pointed out. Furthermore, an overview of current developments regarding sensor and actuator integrated fixtures is given which aim to overcome the challenges of vibrations, deformations and positioning of sensitive workpieces. The presented work makes obvious that a detailed analysis of process-workpiece-fixture interactions is necessary for a proper layout and optimization of fixtures. Finite Element analysis and process simulations provide a significant support for the improvement of the fixture performance. Active fixtures with actuated clamping elements can contribute to more stable process conditions. Consequently, fixtures can be a powerful element of modern machining systems. A detailed investigation of the whole system is essential in order to gain the full potential of innovative fixture technology.

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