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MODULAR INTELLIGENT FIXTURE SYSTEM FOR FLEXIBLE CLAMPING OF LARGE PARTS

In this work a modular intelligent fixture system for flexible clamping of large parts is presented. The fixture modules consist of a hybrid material structure involving metal frame elements and mineral casting. These modules can be combined and connected to realize fixtures adapted to the geometry of the workpiece and requirements of the machining processes. By integrated pipes and interfaces, an internal hydraulic supply and active cooling is possible even for combined modules. Temperature and acceleration sensors allow for an active thermal control and process monitoring. The modules and first test fixtures are investigated in experiments.

1. INTRODUCTION

Fixtures and workpiece clamping systems are an essential part of machining systems [1]. Main tasks of fixtures are to provide a defined position and orientation of clamped workpieces within the workspace of machine tools, to maintain this position and orientation under the influence of static and dynamic forces and thermal loads, and to guide mechanical process loads as a component of the machine tool structure [2]. Further requirements are the accessibility with respect to interference free machining, easy loading and unloading of workpieces, and a workpiece clamping without distortions due to clamping forces [3]. Besides specific fixtures for individual workpieces, which are optimized with respect to particular machining processes, re-configurable and flexible fixture systems are available which allow clamping of a variety of parts [4,5]. Extensive research work addresses strategies for optimizing clamping configurations [6-10]. The dynamic fixture behaviour which affects the process stability has to be considered in particular [11,12].

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The usability of available flexible and re-configurable ‘construction kit’ fixture systems is limited to relatively small workpieces. Clamping of large parts (with characteristic dimensions above 1 m) reveals specific challenges [13]. Large workpieces often possess a considerably high static and dynamic compliance. An appropriate arrangement of clamps and supports is necessary to allow stable machining. Especially for large parts, specifically designed and expensive ‘single use’ fixtures are commonly used. Since large workpieces are often manufactured in small lot sizes or single piece production, costly fixtures become dispensable after a short time of utilization.

Some developments in fixture technology are related to ‘intelligent’ fixtures with integrated sensor and actuator functionality [5,14-16]. Integrated sensors can be used for monitoring the clamping situation (e.g. for safe clamping), the behaviour of the clamped workpiece (e.g. to avoid distortions due to clamping forces), or the process conditions (e.g. to recognize chatter). Although the potential of sensor equipped clamping devices and fixtures has been shown successfully, only few implementations in industrial products can be observed.

2. MODULAR FIXTURE CONCEPT

This paper presents an approach of a modular fixture system for clamping of large parts. Integrated sensors allow measuring of vibrations and internal temperatures. The modular fixture concept involves re-configurable cubic elements, which can be arranged and connected in a setup that is optimized to the clamping and supporting requirements of the workpiece and the machining process. In Fig. 1, besides the principle concept, a simple example of three modules building a clamping tower is shown. The distribution of clamping points, the size of the fixture and its static and dynamic properties can be adjusted by recombining the fixture modules.

In order to achieve an optimized stiffness to mass ratio and high structural damping of each fixture module, a hybrid material approach is chosen. The modules consist of steel frames which are filled with mineral casting. The steel frames provide the connecting interfaces that allow the assembly of the overall fixture. Mineral casting is used due to its material damping characteristics, low density and high compression stiffness [17]. In order to avoid shrinkage clearance during the curing of the mineral cast filling [18], a certain pre-stress was applied in the fabrication of the modules.

The hybrid approach enables an integration of hydraulic pipes and cooling circuits during the mineral casting process. Thus, hydraulic actuated clamping elements can be applied for automated clamping of workpieces in small or medium batch production. The mounting and hydraulic connection of the clamps at the fixture modules involves adapter plates which allow a precise arrangement of the clamping points at the workpiece. In order to realize the internal hydraulic supply and a common active cooling system, fluid connectors are provided at each interface of the fixture modules. Thermal sensors allow internal temperature measurements. Together with the integrated cooling circuits, an actively controlled thermal stabilization of the fixture system can be implemented. By integrated acceleration sensors, fixture vibrations can be measured during machining.

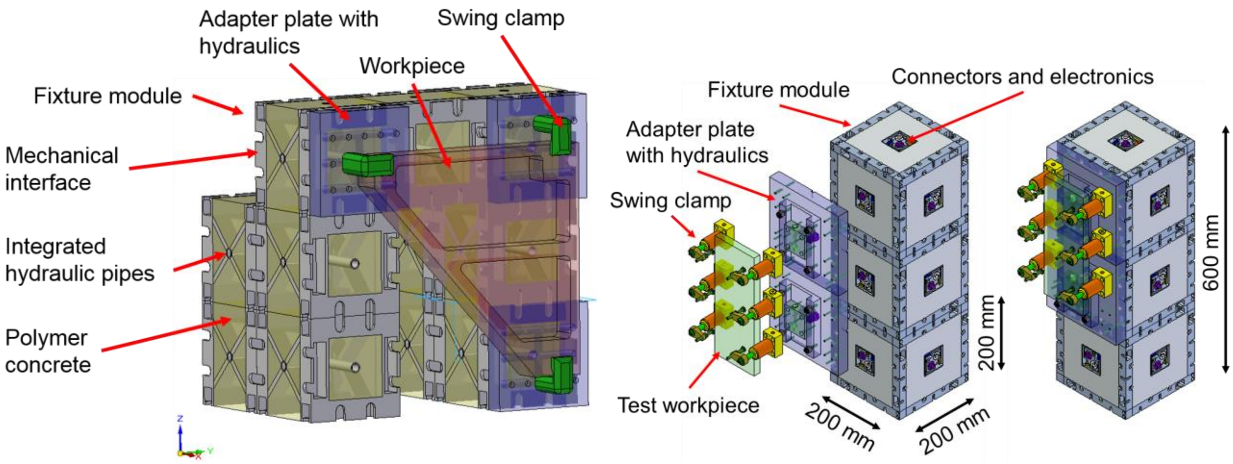


Fig. 1. Modular fixture concept based on cubic elements

3. PRINCIPAL INVESTIGATIONS

Regarding the hybrid material structural approach of the fixture modules a basic task is to select and design appropriate interfaces between the steel frame and the mineral casting. Here, 18 different interfaces were tested with respect to their tensile strength (Fig. 2). In these tests, axial loads were applied until breakage of the specimen. Whereas screws and anchors can provoke crack initiation, shot blasted surfaces provide an acceptable strength. Thus, the effort of integrating additional fastening elements can be avoided.

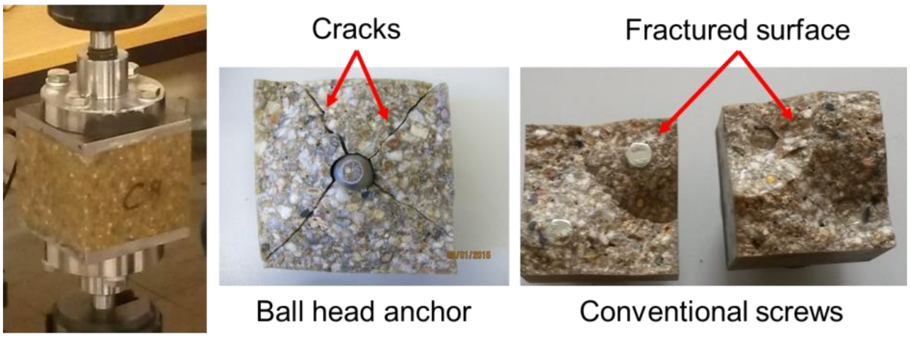


Fig. 2. Tests regarding tensile strength of various material interfaces

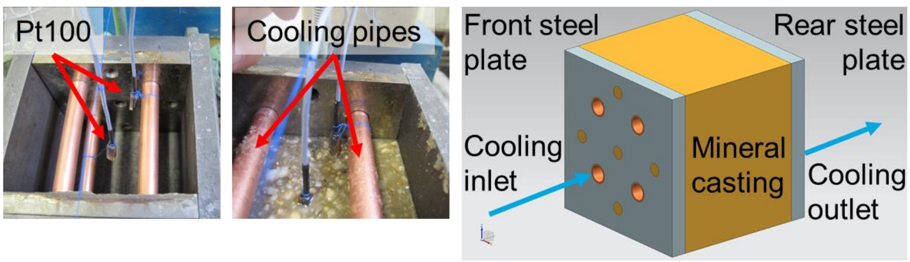


Fig. 3. Test setup for active cooling experiments

For the analysis of internal cooling, test specimen consisting of two steel plates and a mineral casting core with integrated cooling pipes and Pt100 temperature sensors were used (Fig. 3). The capability of the internal sensors regarding the measuring of the core temperature was verified without the application of active cooling (Fig. 4). The measured data of the integrated sensors (PT100 Core/PT100 Plate) were compared to surrounding ambient temperature sensors (NiCr beneath, left, above and right).

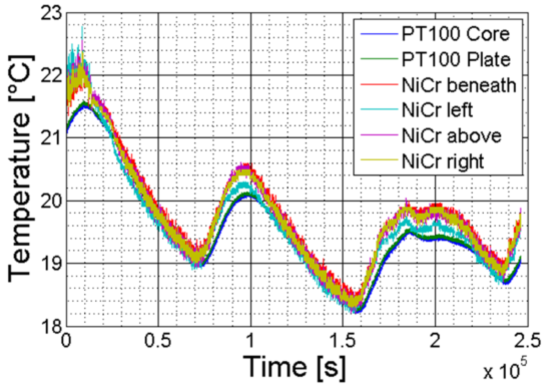
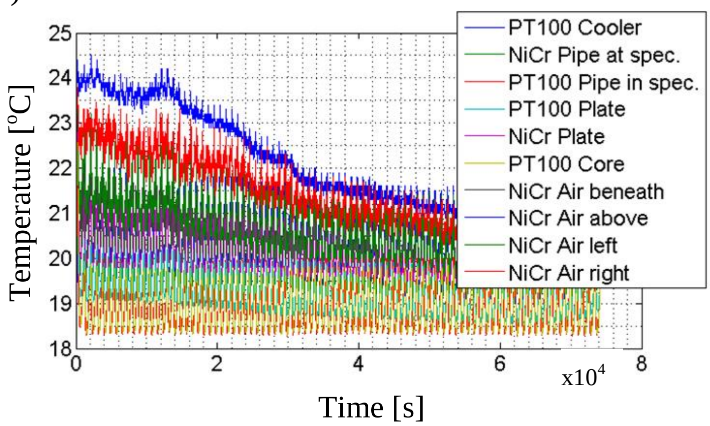


Fig. 4. Temperatures at specimen without active cooling

a)



b)

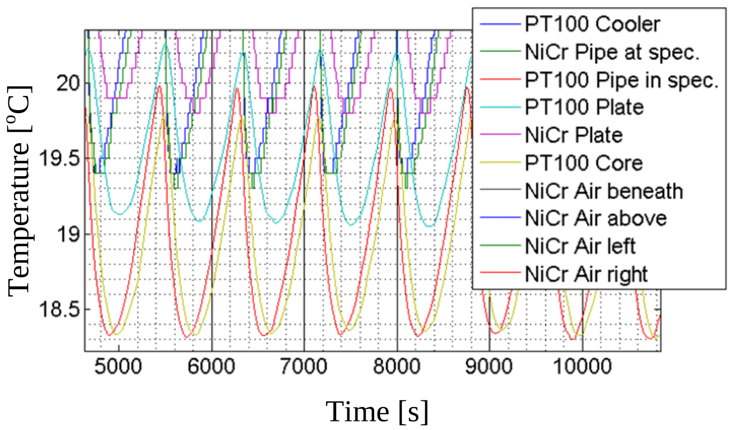


Fig. 5. Temperatures at specimen with active cooling

In further experiments, active cooling was applied and temperature measurements were taken by internal and external sensors (Fig. 5). The internal temperatures (PT100 Pipe in specimen/PT100 Core) could be kept between 18.5°C and 20°C (Fig. 5b).

4. REALIZATION AND ANALYSIS OF MODULAR FIXTURE PROTOTYPE

The design of the fixture modules with integrated piping, sensors and information processing systems is shown in Fig. 6. The modules consist of a steel frame with mechanical interfaces and referencing feather key notches which allow the alignment and connection of multiple modules. The distributed mechanical interfaces enable four bolted connections at each side of the cubic elements. At each side, interface modules carry fluidic connectors for establishing the hydraulic supply and internal cooling throughout an assembled fixture. Coupling of the connectors is provided by mounting two fixture modules together. Otherwise the connectors seal the internal fluidic system. Inside the interface modules, microcontroller boards, Bluetooth modules, SD card adapters and storage batteries are accommodated which carry out the data pre-processing and communication of internal sensor signals. The prototype modules before filling with mineral casting are shown in Fig. 7. Eight temperature sensors and one MEMS acceleration sensor are placed in each module. The fixture modules were tested in stiffness and experimental modal analyses. Fig. 8 shows modal analysis results for using the upper front vertex (point 5) as drive point.

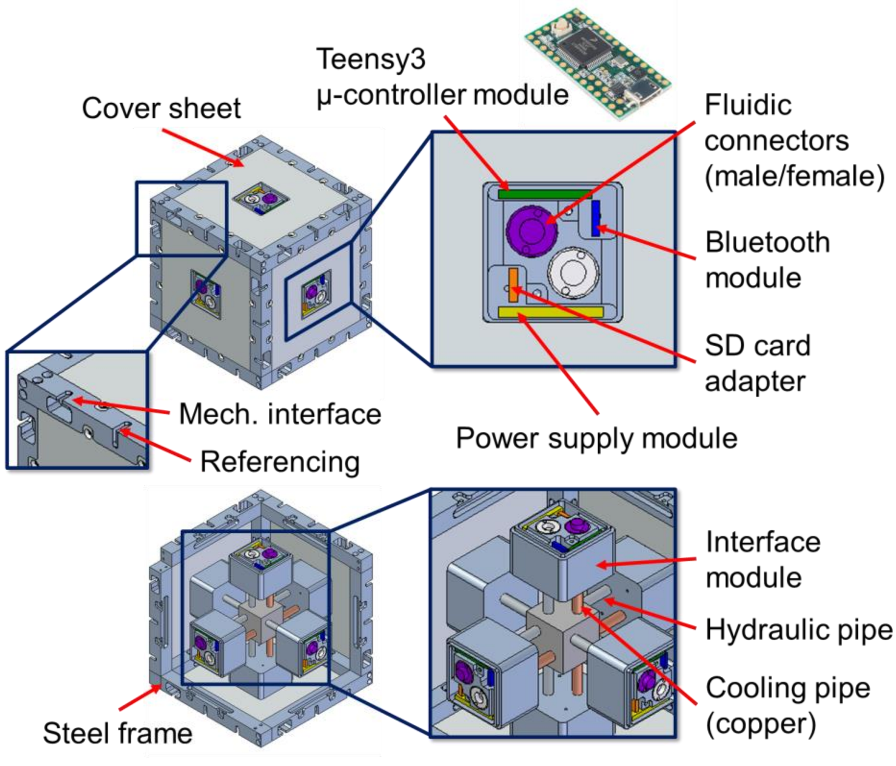


Fig. 6. Design of the fixture modules

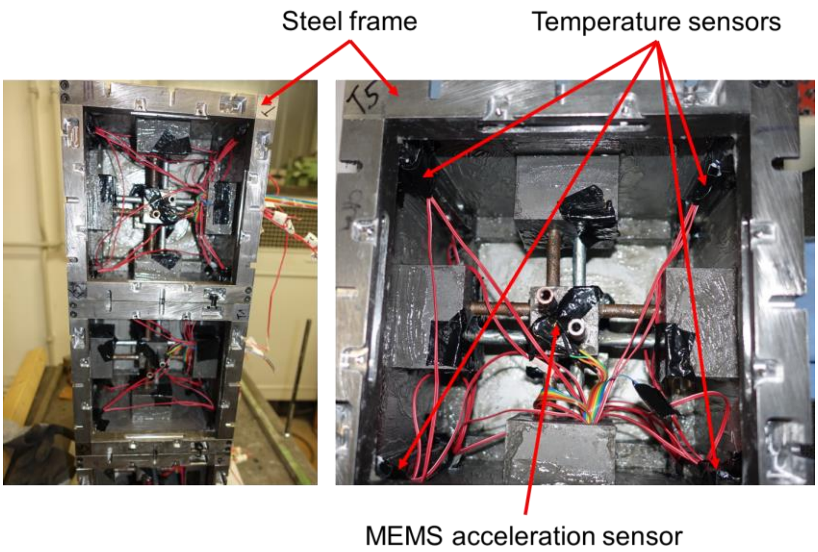


Fig. 7. Mounted modules with integrated sensors before filling

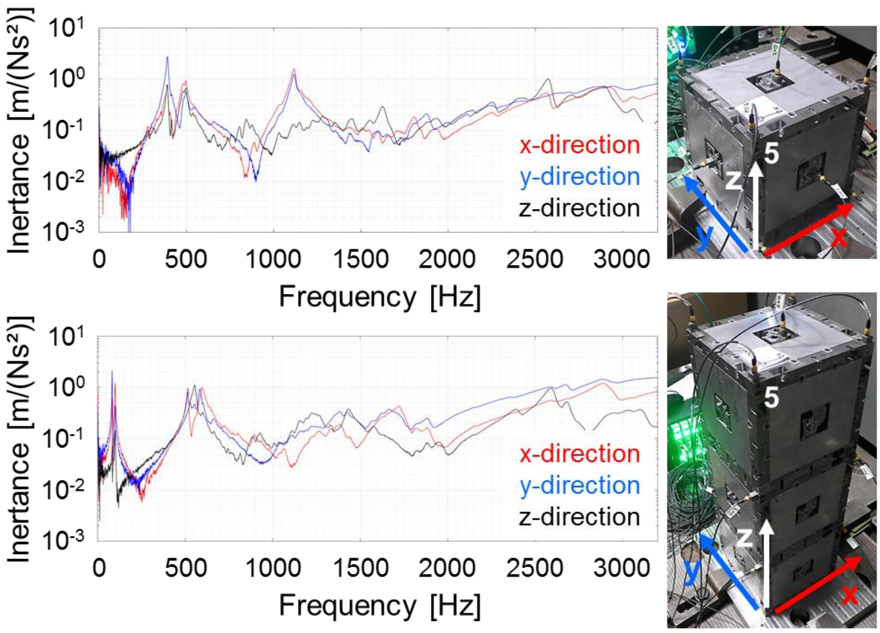


Fig. 8. Modal analysis of single and connected fixture modules

Table 1. Modal analysis results for first three mode shapes

No.	Mode shape	Frequency [Hz]	Damping ratio [%]
1 2 3	Bending in y-direction Bending in x-direction 1st torsional mode	392 490 1,115	1.0 2.6 1.3
1 2 3	Bending 135° with x Bending 45° with x 1st torsional mode	82 100 515	0.7 1.5 1.0

Table 1 summarizes the first natural modes for the single (upper part) and the combined (lower part) modules. Though the single module provides acceptable dynamic stiffness, the first natural frequency of the combined modules is significantly lower. This reveals that further improvement of the mechanical interfaces is necessary.

Together with the dynamic response tests, the capability of the MEMS (micro-electro-mechanical-system) acceleration sensors was analysed (Fig. 9). Here, an Analog Devices ADXL001 MEMS sensor was used and compared to a Brüel&Kjaer 4524B reference sensor. The MEMS sensor allows the identification of dominant vibration frequencies and can therefore be used for some monitoring purposes. However, a low signal-to-noise ratio is obvious. Depending on the requested sensitivity, either the low cost MEMS sensor or a sophisticated acceleration sensor can be mounted into the modules.

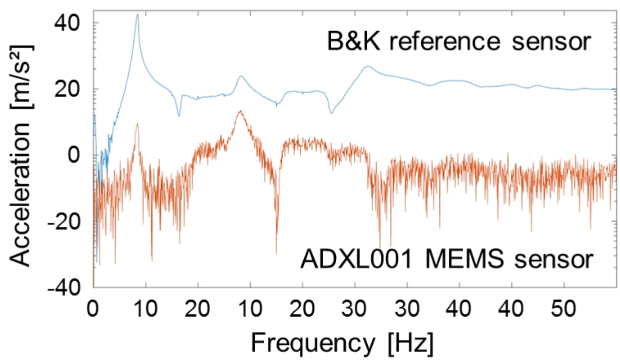


Fig. 9. Comparison of MEMS sensor with a reference sensor

Furthermore, the effect of active cooling of the fixture modules was investigated in basic tests. For this, fan heaters were placed next to the arrangement of three combined modules and measurements of temperatures and displacements were conducted (Fig. 10). Without cooling, the temperatures at the outer surfaces of the modules exceed 40°C and displacements above 0.2 mm occur. When active cooling is applied, the relevant temperatures can be reduced to 30°C and displacements are below 0.1 mm. Since the cooling pipes inside the prototype elements are short and no cooling coils are used, the cooling effect is limited. However, the principle functionality is approved.

The prototypic modular fixture was placed at a clamping table of a large milling machine in order to allow experimental testing under real process conditions (Fig. 11). The fixture modules were connected to build a clamping tower with an overall height of 600 mm. This configuration allows a comparison with conventional fixtures in subsequent studies. For the clamping of larger parts even more modules with the size of the realized prototypes could be combined. On the other hand, for workpieces with dimensions of several meters, an up-scaled variant of the modular fixture approach shall be applied which provides larger cubic modules and less interfaces. The scaling effect and influence on the layout of the steel frame and mineral cast filling is not investigated up to now. Furthermore, an optimisation and assessment of the size of the modules versus the necessary number of interfaces in a large scale fixture has to be considered in following development steps.

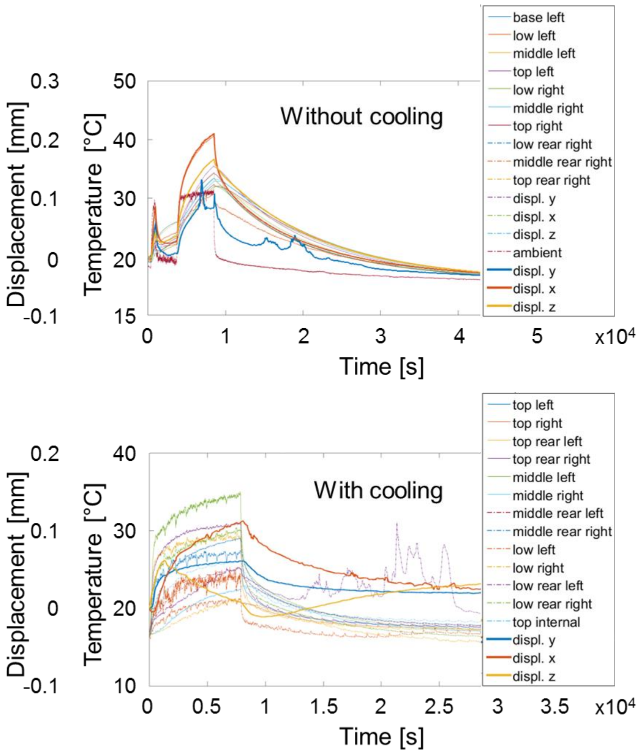


Fig. 10. Thermal analysis of fixture modules with and without cooling

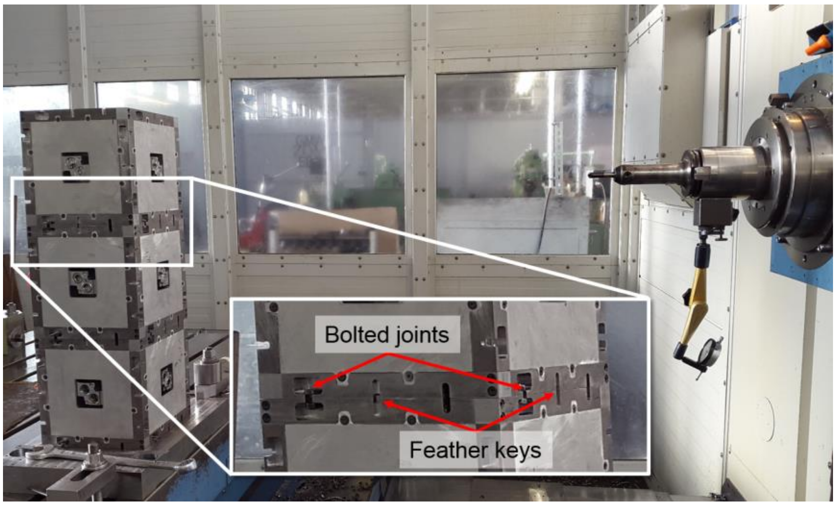


Fig. 11. Integration of modular fixture inside a milling machine for machining tests

The assembly of the fixture in this setup utilizes 4 bolted joints which are allocated to the interfaces between the frame components of two modules. In addition, by the use of feather keys, the modules are adjusted to each other. This arrangement turned out to be acceptable for a first functional verification of the general approach. However, a further improvement of the design of the interfaces and joints is necessary and subject of future work. For machining tests, the modular fixture prototype was equipped with adapter plates and hydraulic clamps as already depicted in Fig. 1 (Fig. 12). Milling of pockets and drilling into an aluminium (Al7075) test workpiece was carried out with different process parameters (Table 2). A 12 mm milling cutter with 3 cutting edges and a 11 mm drill were applied. Vibration measurements during the machining tests show, that stable process conditions can be provided by the prototype fixture with the applied process parameters (Fig. 13).

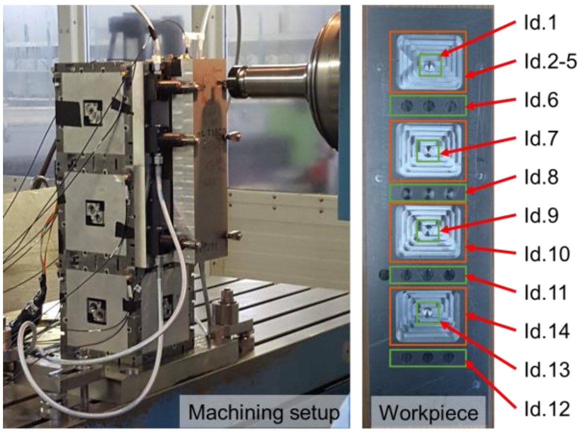


Fig. 12. Setup for machining tests and features at test workpiece

Table 2. Process parameters during machining tests

Id.	Process	n [min^{-1}]	v_f [mm/min]	a_p [mm]
1	Drilling	2.895	345 / 690	-
2	Milling	3.448	690	1
3	Milling	3.448	690	1.5
4	Milling	3.978	796	3
5	Milling	3.978	1.380	3
6	Drilling	2.895	579	-
7	Drilling	2.895 / 3.978	579 / 1,380	-
8	Drilling	2.895	579	-
9	Drilling	2.895 / 3.978	579 / 1,380	-
10	Milling	3.978	1.380	9
11	Drilling	2.895	579	-
12	Drilling	2.895	579	-
13	Drilling	2.895 / 3.978	579 / 1,380	-
14	Milling	3.978	1.380	9

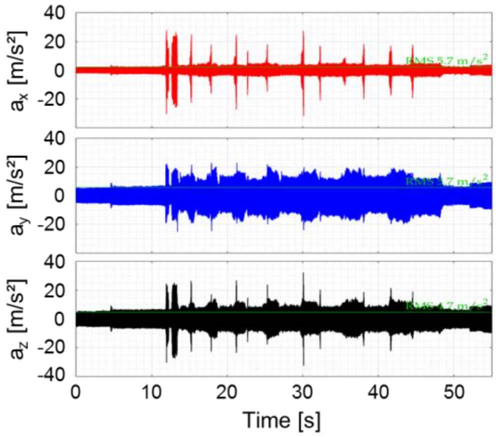


Fig. 13. Vibrations during machining of pocket Id.5

5. SUMMARY AND CONCLUSION

This paper presents a novel modular fixture system which allows flexible re-configuration and combination of basic fixture elements in order to create clamping setups for large workpieces. By this means, optimized fixture properties with respect to workpiece support and process performance can be achieved. Integrated hydraulic piping and connectors enable application of automated clamping elements. Active cooling can be provided by coupled internal cooling circuits. The integration of the fluidic systems allows avoiding external pipes or tubes. Acceleration and temperature sensors inside the fixture modules, enable process monitoring and temperature control. A hybrid material structural approach is chosen which exploits the advantageous material properties of mineral casting and steel. System integration can easily be conducted during the mineral casting process. Experimental analyses show the characteristics of the realized prototype regarding dynamic stiffness and thermal behaviour. The functionality of integrated sensors is verified. In machining tests, stable cutting conditions could be observed. Thus, the new approach could be approved. The results also reveal potential for improvements and challenges for subsequent research work.

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