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Process chains for high-precision components with micro-scale features

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ABSTRACT

This keynote paper addresses the manufacturing of high-precision components with micro-scale features, and the associated process chain considerations. Three workpiece classifications as well as a micro-production process chain (MPPC) model are defined. A review of capabilities and advances in micro-manufacturing technologies, metrology, and equipment demonstrates increased versatility across varied applications, while also highlighting limitations. Challenges in the development of process chains are presented using results of the MPPC program of the Collaborative Working Group on Micro-Production Engineering. Finally, a guide for machining high-precision components with micro-scale features in process chains is given with respect to machine tools, tools, technology and environmental conditions.

1. Introduction

The production of high-precision components with micro-scale features is of growing importance in almost all industrial sectors and scientific disciplines. Components with high macroscopic and microscopic complexity range from individual components such as spectrometers to high volume optoelectronic components. Irrespective of production volume, the chosen technologies have to meet all productivity and quality criteria, i.e. reliability, cost, reproducibility, and accuracy of key geometric elements. Verification of these criteria requires a metrology capable of resolving micro-scale features. To remain consistent with the definition of micro-metrology provided by Hansen et al. [103], micro-scale production is defined as the production of goods with at least one critical dimension or at least one function-critical tolerance in the range of single micrometers.

The CIRP community has been active in this industrially relevant arena with many keynote papers exploring different aspects of micro-machining and metrology, i.e. micro-machining [173], micro-forming [91], micro-engineering [5], mechanical micro-machining [69], and dimensional micro- and nano-metrology [103]. Similarly, other CIRP sponsored conferences, precision engineering societies as well as national and international research networks are also focused on researching and exploring new opportunities for the production of micro-featured, high-precision components. However, to date only few publications provide a holistic overview of the manufacturing process chain elements required to successfully produce and qualify these types of components. In this paper the shortcomings of the classical process chain model with respect to micro-featured, high-precision components is briefly discussed and a new micro-production process chain (MPPC) model, which is a direct outcome of the Collaborative Working Group (CWG) on Micro-Production Engineering, is introduced, see Section 2. The results of the MPPC program of the CWG on Micro-Production Engineering showed that process chains can be built through the collaboration of various manufacturing facilities. This offers new opportunities for world-wide networks using decentralized expertise and standard procedures instead of local concentration. The proposed model also offers the potential to predict the expected level of manufacturing complexity associated with different components. Details of the three different levels of component complexity (Classes I, II and III) are provided in Section 3. Section 4 will outline how process developments in different technological areas are increasing the potential to manufacture micro-scale geometries with higher complexity or relatively simple micro-scale geometries more efficiently. Section 5 will specifically outline the challenges associated with the metrology of micro-scale features and will include a discussion of current metrology systems and their limitations. Section 6 will discuss the basic machine tool requirements for the precision manufacturing of micro-scale geometries, the advantages and the increased need for hybrid machines, built-in machine tool metrology, and advanced workpiece holders. Section 7 introduces the results and findings of a

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MPPC program spanning over three years between multiple organizations, managed by the TU Berlin, to investigate potential process chains for manufacturing of a Class II component. The knowledge gained in the program supports the proposed MPPC model and highlights core strategies and technologies in the manufacture of multiple micro-scale features on a high-precision component. Finally, Section 8 will provide a summary and an outlook for future needs in micro-production engineering.

2. The proposed micro-production process chain model

The classical process chain model follows the principle "from rough to ultra-precise machining" [69], often with just one final metrology stage, Fig. 1(a). This approach is only suitable for a small range of micro-featured, high-precision components where the required geometrical features can be generated through independent machining operations. As the component complexity increases, the process chain must accommodate more processes, tool set-ups, intermediate measurement steps, and perhaps even fiducial mark manufacturing to guarantee sufficient position accuracy of the features. The outcomes of the Collaborative Working Group on Micro-Production Engineering confirmed this and therefore a MPPC model is introduced, Fig. 1(b). With increased complexity more manufacturing-metrology iterations are required.

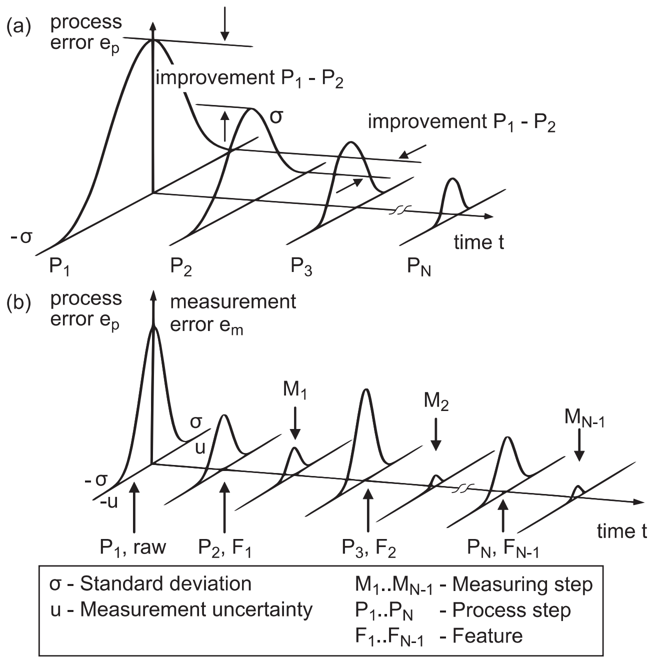

Fig. 1. (a) Classical process chain [70], and (b) micro-production process chain model.

The ability to successfully machine features occurring later in the process chain depends significantly on the quality of initial reference surfaces and geometric features. The final process step does not need to be the most precise manufacturing step. The intermediate metrology steps may include measurements of the component or its position in the machine tool. Minimizing the number of manufacturing-metrology iterations through the use of hybrid machines and specialized fixtures can significantly reduce manufacturing complexity, geometric errors, and overall process times. However, specialized equipment is of course costly. If multiple machine set-ups are unavoidable, then the necessity for intermediate metrology steps implies that subsequent processes must not be undertaken within the same facility. This offers interesting opportunities for world wide networks using decentralized expertise and standard procedures to manufacture complex components.

3. Examples of products with micro-scale features

Products with micro-scale features are common in a broad range of industrial applications, such as optics, automotive, energy, and biomedicine. They also encompass a widespread spectrum of manufacturing and metrology technologies. The samples selected here will serve to illustrate requirements and opportunities for current and future production processes [63]. The sample components are considered with respect to the complexity of their process chains. In this context the complexity increases with an increasing number of geometrical features (i.e. required number of processes), relative positional accuracy between multiple features, and the number of relevant workpiece surfaces.

3.1. Class I: Single machine tool set-up

3.1.1. Class I characteristics

The features may be either simple or complex, e.g. channel versus 3D structure, and can be manufactured in one working operation. The required positional, dimensional and form accuracy can be achieved with a single machine tool.

Product examples are micro-fluidics, Fresnel optics, diffraction gratings, stents, injector nozzles, eye clamp devices, micro-pore X-ray mirrors, impellers, and medical needles (Fig. 2). Many of these products are commercially available and current manufacturing technology is sufficient to meet the quality criteria of such components.

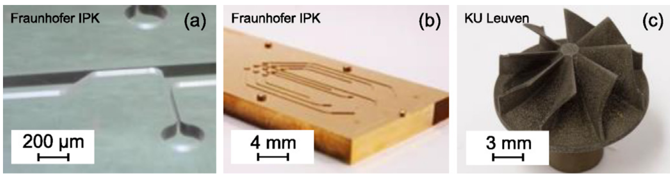

Fig. 2. Class I parts; (a) micro-fluidic chip for blood plasma separation, (b) hot embossing tool for fog sensor, and (c) gas turbine impeller [166].

3.2. Class II: Multi-machine tool set-up

3.2.1. Class II characteristics

Different features call for different processes and machine tools on one or more surfaces. The workpiece has to be realigned or placed on an additional machine tool, thus losing the machine tool-workpiece relative alignment. Intermediate metrology steps are necessary to ensure quality compliance. The Process Chain Model to successfully manufacture these types of components is shown in Fig. 1(b). Class II components can be converted into Class I components by utilizing hybrid machine tools, universal clamping systems, and innovative, component-specific clamping systems. Of course a trade-off between machine costs and machining time exists.

Examples for Class II parts are complex micro-tools and molds, high-class clockwork frames, hybrid lenses, bi-conic air bearings, laser lenses, particle accelerator parts and vitrectomy devices (Fig. 3).

The manufacturing of one micro-scale structure on a defined surface is done on a regular basis. Combining processes to create different micro-scale features relative to each other is much more challenging. This is also due to the fact that previous and

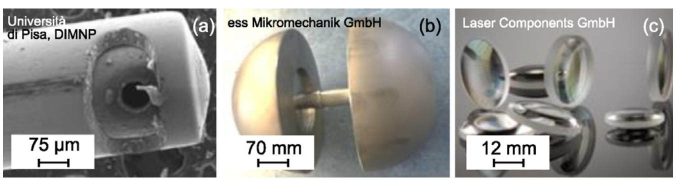

Fig. 3. Class II parts; (a) vitrectomy device [83], (b) bi-conic air bearing, and (c) glass lenses for laser beam formation.