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Fiber-reinforced Fused Filament Fabrication for diamond cutting tools

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Abstract

Additive manufacturing technologies open up new possibilities for the production of highly complex and geometrically flexible components. The reduction of material accumulations and single parts as well as the integration of lattice and numerically simulated structures enable a type of lightweight construction that is unattainable with conventional manufacturing processes. Furthermore, the integration of inserts during the process enables local reinforcement. Therefore, additive manufacturing processes are already being used in aerospace technology, the automotive sector and in mold and die making industry. In addition, Fused Filament Fabrication (FFF) enables the integration of continuous fiber-reinforcement into components made of carbon short fiber-reinforced polyamide. This technology provides mechanical strength properties that allow the substitution of aluminum. In this study, the possibilities resulting from these process properties were investigated for the manufacturing of diamond cutting tools. For this purpose, different flycutter geometries were developed to be manufactured by dual fiber-reinforced FFF. The geometries were evaluated regarding their suitability for the application in ultra-precision machining. A finite element analysis was carried out to analyze the deformation of a suited fly cutter geometry during use in dependence of the integrated content of continuous fiber. A reduced displacement for continuous fiber-reinforcement parts could be demonstrated which implies a higher stiffness due to the reinforcement superposition. Furthermore, eigenfrequency calculations showed that a higher content of fiber-reinforcement results in an improved deflection of the vibrations during use. These findings provide a basis for future research in the field of FFF-based manufacturing of diamond cutting tools. This offers the opportunity to adapt them more easily to individual requirements and enables a more cost-effective tool production with shorter iteration cycles.

Keywords: fiber-reinforcement Fused Filament Fabrication, FEM simulation, ultra-precision machining tools

1. Introduction

Additive manufacturing (AM) enables the implementation of complex structures, short lead times and the economical production of small batch sizes. Due to these properties AM technologies have become established in an increasing number of areas like aerospace technology, the automotive sector as well as production technology including tool and mold making [1]. In this sector, AM has been used primarily for the production of casting molds [2]. Novel advances in AM open up new potentials to build lightweight and stiff tools for ultra-precision machining by implementing numerically simulated geometries and integrating superimposed fiber-reinforcement during the manufacturing process. The AM-technology Fused Filament Fabrication (FFF) enables the integration of continuous fiber-reinforcement during the manufacturing process. During the build job a continuous fiber coated in fusible resin is placed between the layers of the component by a second nozzle. A carbon short fiber-reinforced polyamide serves as matrix material which leads to a superposition of continuous and short fiber-reinforcement. This process facilitates the production of extremely lightweight components with high rigidity and strength through the integration of complex structural elements and undercuts [3]. This potential can be increased by using numerical simulations to develop complex geometries that allow a reduction in material while maintaining a high rigidity of the component [4, 5].

2. Experimental setup

2.1. Development of the tool geometry

To investigate the potentials dual fiber-reinforced FFF opens up for ultra-precision machining, four different tool geometries of a flycutter were developed considering the manufacturing guidelines for FFF. Reinforcement and cross brace structures resulting from topology optimization analysis were implemented into the tool geometries in order to reduce material while keeping the stiffness at a maximum to fulfill the requirements for ultra-precision machining tools. To analyze the response of the geometries to mechanical loads, Finite Element Method (FEM) simulations were carried out. All numerical simulations were carried out using the software INSPIRE by ALTAIR, Troy, United States.

The developed tools were to be mounted on an ultra-precision spindle, the tool dimensions were set accordingly. Two different shaft-hub connection concepts were examined for the assembly. All developed geometries were designed in the CAD software NX by SIEMENS DIGITAL INDUSTRIES SOFTWARE, Plano, USA. To analyze the printability of the tool geometries they were manufactured on an ONYX PRO FFF-printer by MARKFORGED INC., Waltham, United States, using carbon short fiber-reinforced polyamide (PA 66) with an embedded continuous glass fiber, both by MARKFORGED INC., Waltham, United States. All components were printed with an infill density of d_i = 100 % and a layer thickness of d_l = 0.1 mm. The most suitable geometry was identified on the basis of the results of the numerical simulations and the feasibility for FFF manufacturing, taking into account the impact on the ultra-precision machining process. Therefore, the factors of balancing, weight, manufacturing effort, ease of mounting, material and machining volume were considered within the scope of a utility value analysis.

2.2. Numerical analysis

To investigate the mechanical behavior, the tool geometry was subjected to a mechanical analysis using finite element analysis (FEM). This includes the calculation of the of the expected displacement under load as well as the determination of the eigenfrequencies. To consider the influence of continuous fiber-reinforcement simulations with and without glass fiber-reinforcement were carried out. For each simulation a cutting force of $F_c = 10$ N was applied, a minimum element size of $A_{e,min} = 0.1$ mm and an average element size of $A_e = 0.5$ mm was used for the calculation. The resulting displacement and eigenfrequencies of the simulations are shown in figure 1.

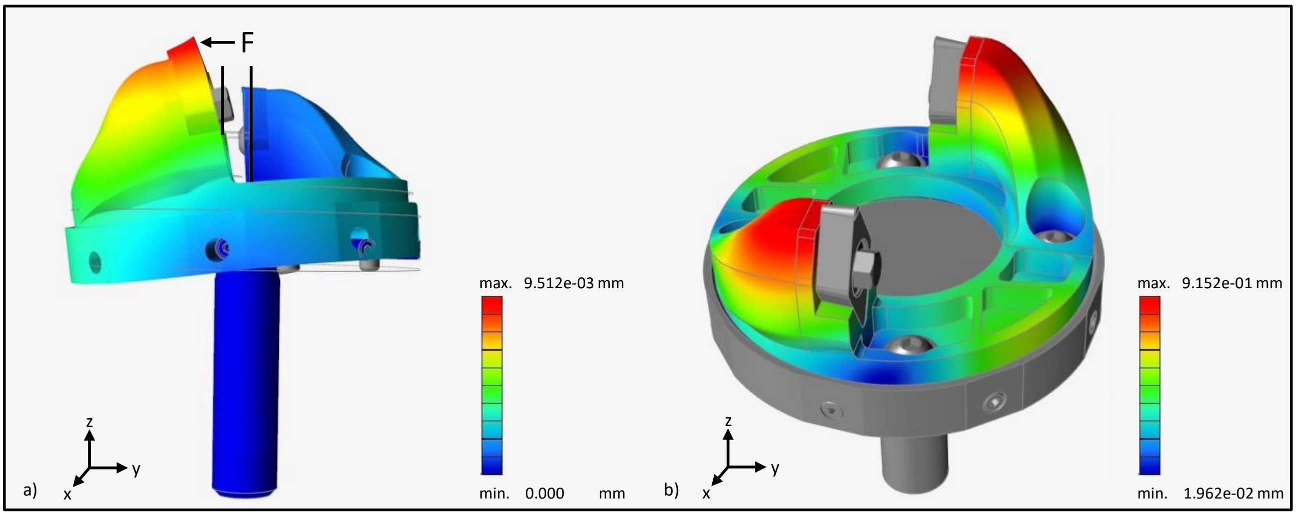

Figure 1. Results of the numerical analysis of the flycutter with integrated continuous fiber-reinforcement; a) displacement; b) eigenfrequencies

At applied load, the simulation showed a significantly greater maximum displacement of $\Delta L_{max} = 9.5$ µm for the tool without continuous glass fiber-reinforcement. Under the same conditions, a maximum displacement of $\Delta L_{max} = 2.6$ µm resulted for the continuous fiber-reinforced components. For these components eigenfrequency simulations also resulted in improved deflection of the vibrations during use compared to simulations not considering continuous glass fiber-reinforcement. Figure 2 shows the additively manufactured flycutter in a process environment.

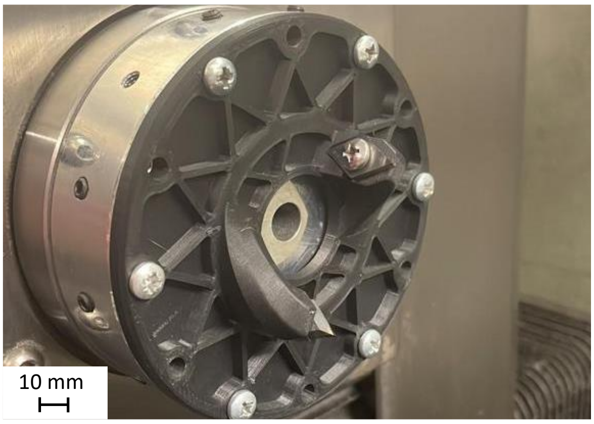

Figure 2. Additively manufactured flycutter mounted to the spindle of the ultra-precision machine tool

3. Conclusion

The findings of this ongoing research show the potential additive manufacturing holds for a more cost-effective tools production in ultra-precision machining. With the development of a tool geometry optimized for fiber-reinforced FFF a basis for a lightweight and rigid flycutter geometry could be introduced. The simulations demonstrated the potential of superimposed fiber-reinforcement in additively manufactured components and provided new approaches for the further development of tool geometries. Compared to conventionally manufactured flycutters, significant material savings and the possibility of implementing complex geometries with local reinforcement were demonstrated. This results in the possibility of adapting tools for ultra-precision machining to individual requirements faster and more easily. The choice of materials and the optimized geometry make it possible to manufacture these tools more cost-effectively and with shorter iteration cycles. Due to the vibrations and deflections that occur during machining, a reduction in surface quality and changes in the effective rake angle γ_0 are to be expected. These challenges need to be addressed in future research.

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