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DEVELOPMENT OF A TOOL-CHANGING SYSTEM FOR NANOFABRICATION MACHINES

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ABSTRACT

The frequent use of a growing diversity of tools in nanofabrication machines raises the need for a highly reproducible tool-changing system that is capable of working with tools of different weights and moments of inertia. Since the tool-changing system is designed beneficially based on an open, force-paired kinematic coupling, means to apply a holding force are required. The holding force needed is about 40 N in total and has to be applied without heat dissipation or other disturbances. Since variations in the elastic deformation at the contact points of the coupling directly influence the reproducibility of the tool position, the force application needs to be highly reproducible.
An analytical model is developed to determine the force application requirements, taking into consideration elastic deformation and friction. Based on this model, the allowable variation of the holding force in amount and direction, as well as the allowable deviation of the force application point, are determined. Thereby, the resulting influence of the force application on the reproducibility of the position of the tool-center point is intended to be 5 nm or less. Eleven solution principles for force application are developed based on the physical effects of magnetic force, spring force, and weight force. Based on a systematic evaluation, an arrangement of three permanent magnets with flux guide pieces at an angle of 120° to each other has been chosen at the fixed side. On the tool side, ferromagnetic plates are used to close the magnetic circuit. Thereby, the air gap and, thus, the holding force can be adjusted individually for each tool. During the tool change, the magnetic force is switched off by short-circuiting the magnetic flux with an additional rotatory-mounted flux piece, which is driven by a gear motor. The designed prototype will be tested and further optimized within a nanofabrication machine.

Index Terms - reproducible force application, tool-changing system, kinematic coupling, nanofabrication

1. INTRODUCTION

The nanopositioning and nanomeasuring machines developed at the Technische Universität Ilmenau require a highly reproducible tool-changing system due to increasing requirements and an extension for nanofabrication [1]. This is realized with a statically determined kinematic coupling that promises excellent capability for the tool-changing system. It ideally consists of six open force-paired point contacts, which can be designed as three ball-V-groove pairings (see Figure 1) or as a combination of ball-tetrahedron, ball-V-groove, and ball-plane pairing. The tools in the nanofabrication machine are mounted against the weight force, requiring an operating force consisting of the combination of the weight force of the tool and a preload force for the kinematic coupling. Therefore, in addition to the position definition, a highly reproducible force application is required since changes in the elastic deformations at the contact points directly influence the reproducibility of the position. The three-dimensional reproducibility of the tool center point position should be less than 50 nm.

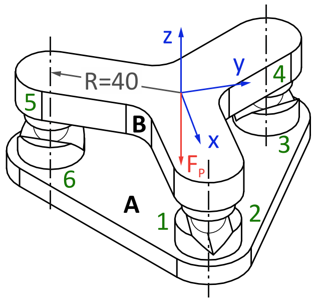

Figure 1. An exemplary design of a kinematic coupling with (A) fixed coupling half and (B) moving coupling half [5]

Tool changing systems with force applications are known in state of the art from (micro-) coordinate measuring machines, although the reproducibility has never been investigated in the required range [2, 3]. The achievable reproducibility of the kinematic coupling for position definition is determined in a separate experimental setup and published in a separate paper [4].

2. REQUIREMENTS FOR THE TOOL-CHANGING SYSTEM

To achieve the highest reproducibility of the kinematic coupling, a defined preload force between the two coupling halves is required to overcome surface effects. The operating force is the result of the weight force of the tool and the preload force and needs to be applied without heat dissipation or other disturbances. In total, this operating force is approximately 40 N, whereby up to 20 N falls to the preload force.
Any deviations in the amount and direction of the operating force cause a change in elastic deformations at the contact points of the kinematic coupling and thus directly influence the reproducibility of the position. The permissible deviations of the operating force are determined based on an analytical calculation model [5] considering the elastic deformations and friction at the six contact points. The influence of the application of the operating force on the reproducibility of the position of the kinematic coupling is intended to be less than 5 nm in total. This results in a permissible deviation of the amount of the operating force of 80 mN, a permissible deviation of the direction of 2.4’, and a permissible deviation of the force application point of 16 µm with equal distribution. Since it is assumed that the tool must be initially calibrated, these are relative deviations between tool-changing operations.

3. DEVELOPMENT OF SOLUTION PRINCIPLES

For force application, a total of eleven solution principles are developed based on the underlying effects of springs, magnets, or gravity (see Figure 2). The evaluation and comparison of the principles consider the influence of the operating force on the reproducibility of the position immediately after the tool-changing process, as well as the long-term influence. The requirements for these principles are the lowest possible influence on reproducibility directly after the tool-changing process and the long-term influence. The reproducibility and the influence of the force application point as well as the gradient of the force-displacement characteristic, are also considered. Due to possible side effects, the tool change must be carried out as impulse-free as possible and further influences on the nanofabrication machine must be avoided or kept to a minimum. The limited installation space defined by the metrological frame of the nanofabrication machine needs to be respected as well. The best principle resulting from this evaluation is the combination of a permanent magnet with a movable flux piece. This allows a smooth transition of the working force to be realized (Figure 3).

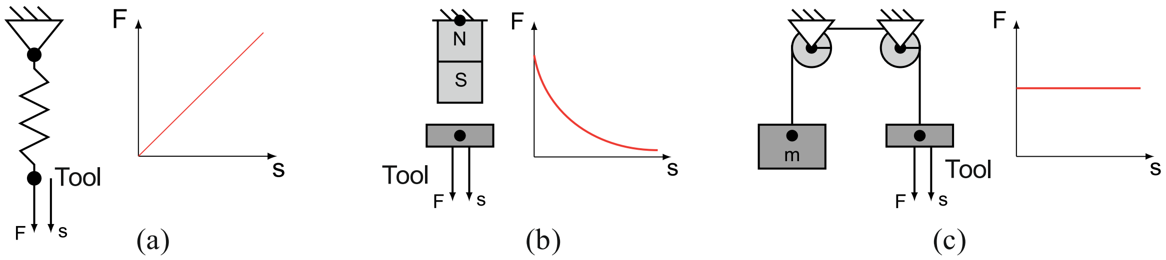

Figure 2. Underlying effects for the solution principles with the force-displacement curves (a) compression/tension springs, (b) permanent magnets, (c) weight force

Compared to the other principles, no disturbing creep effects are to be expected, such as when using springs. The gravitational load on the metrological frame of the nanofabrication machine is lower than when using a counterweight. Due to the movable flux piece, an almost impulse-free tool-changing process can be expected. A constant force is guaranteed over a wide angle of rotation of the flux piece. An inverse design, where the tool is held by the weight force, is not pursued further due to several disadvantages. These include a more complicated coupling process, a lower stiffness of the tool-changing system, and limited adaptation to tools with different weights and moments of inertia.

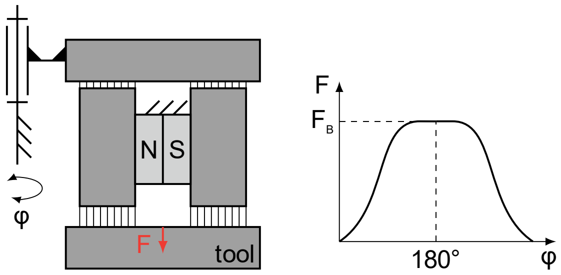

Figure 3. Solution principle consisting of a permanent magnet and a movable flux piece for switching the magnet during the tool-changing process [6]

4. CONCRETIZATION AND DESIGN OF THE SELECTED SOLUTION

For the function of the nanofabrication machine, a free aperture of the tool-changing system with a diameter of 20 mm is required. Therefore, it is not possible to apply the force in the center of the tool-changing system, and an arrangement of three times 120° is used for the magnetic circuits. The magnet configuration is realized with an axially magnetized magnet plate made of NdFeB as well as two flux guide pieces (see Figure 4). The required dimensions of the magnets and the dimensioning of the air gap were determined using analytical and subsequent numerical finite element calculations. With a dimension of the magnets of 10x10x3 mm³ and an operating air gap of 0.7 mm, a force of 13.3 N per magnet circuit is obtained. Using a short-circuit air gap of 0.1 mm, the combined force of the magnets can be reduced to 12 N, which is less than the weight force of the tool side. Since the entire tool-changing system becomes a part of the metrological frame of the nanofabrication machine, all components are made of the low thermal expansion alloy Invar. As this material shows ferromagnetic behavior, the magnetic circuits are isolated by encapsulation in aluminum.

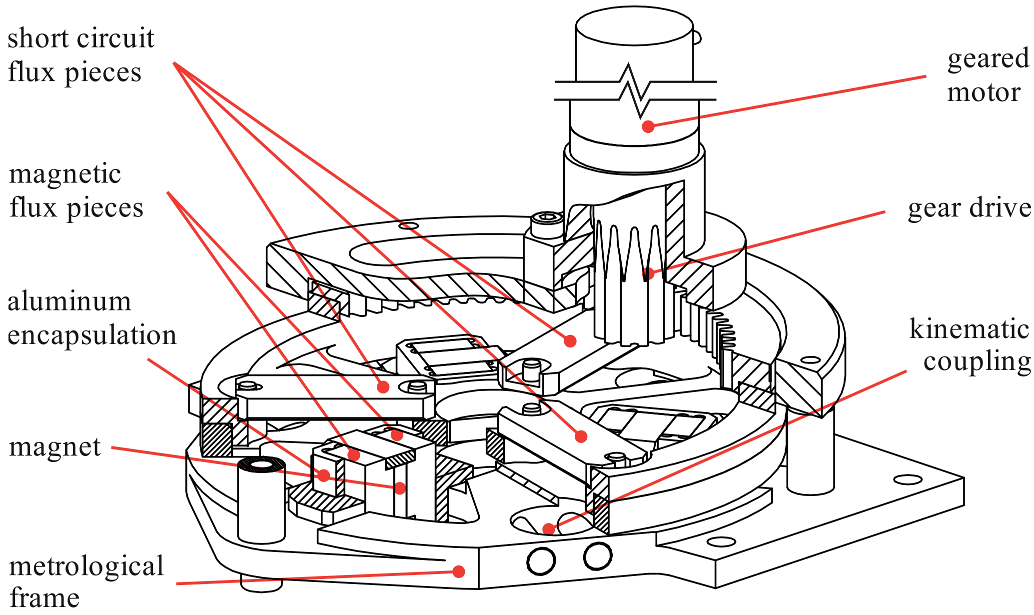

Figure 4. Design of the fixed side of the tool-changing system

A joint rotatory movement of all short-circuit flux pieces is chosen for simplicity. The actuation is carried out using a vacuum-compatible geared motor with an additional gear drive used to generate the actuating torque of 3.5 Nm.
The operating air gaps of the three magnetic circuits and, thus, the amount and direction of the operating force can be adjusted (see Figure 5). This adjustment is required as the mass and position of the center of gravity are different for each tool used. The adjustment is realized by placing thin spacer elements with a minimal thickness of 50 µm under the flux pieces, which are fixed with screws. Since this adjustment needs to be made individually for each tool, it is located on the tool side.

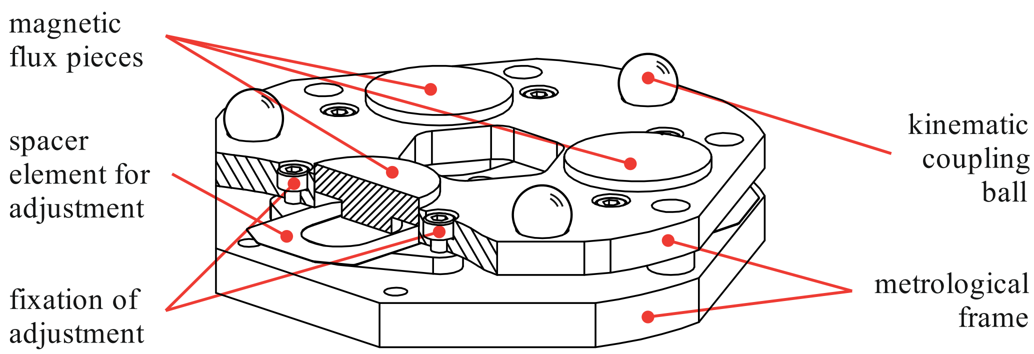

Figure 5. Design of the tool side of the tool-changing system

5. SUMMARY AND OUTLOOK

The development of a tool-changing system for nanofabrication machines presented here focuses on a highly reproducible force application. The solution selected is a permanent magnet combined with a movable flux piece. In this solution, the air gap and, thus, the amount of the force, as well as the angle of the force application, only depend on the reproducibility of the position definition. Since this is realized by a kinematic coupling, the requirements regarding the amount and angle of the operating force can be fulfilled. When using magnets, the position of the force application does not influence the operating force.
The next steps are to complete the investigations on the position definition with the developed measurement setup [4]. The first results show that the targeted reproducibility of the tool-changing system of 50 nm can be fulfilled by the kinematic coupling. Due to the influence of the force application on the reproducibility of the position, a prototype of the tool-changing system needs to be investigated within the nanofabrication machine for its achievable reproducibility of the position.

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