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Kinematic fixtures to enable multi-material printing and rapid non-destructive inspection during two-photon lithography

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ABSTRACT

Two-photon lithography (TPL) is a polymerization based technique that enables additive manufacturing of millimeter scale parts with submicron features. TPL equipment is often based on retrofitted optical microscopes that lack precise registration capabilities. Consequently, slow and error-prone visual alignment to fiducials is necessary if registration to pre-existing features is required. Herein, we have designed, built, and tested precise kinematic fixtures that are repeatable to within ± 315 nm (3σ value) and passively register the build surface to TPL equipment with an accuracy of ± 1.7 µm. This enables one to sequentially print with multiple materials by building the structures directly on top of the kinematic fixtures. In addition, the same fixtures passively register to an X-ray computed tomography (CT) system to enable non-destructive 3D inspection that is integrated with the fabrication process. These fixtures (i) provide a practical means to handle micro-scale parts during non-destructive imaging, (ii) reduce the set-up time for X-ray CT from more than an hour to less than a few minutes, and (iii) eliminate operator uncertainty from the multi-material printing and imaging process. As such, these fixtures enable new printing and imaging functionalities that are critical for high-quality additive manufacturing of multi-material polymer parts with microscale and submicron features.

1. Introduction

The ability to precisely register parts to processing and metrology equipment is a key manufacturing capability that differentiates benchtop laboratory-scale experiments from industrial-scale production. In the absence of this capability, it is impossible to automate and integrate a fabrication process into a manufacturing system. Unfortunately, several emerging advanced manufacturing technologies are currently lacking this capability. Herein, we have used the two-photon lithography (TPL) process as a case study to demonstrate how precise registration can enable new printing and integrated inspection capabilities that are critical for high-quality additive manufacturing. Specifically, we demonstrate the role of precise fixtures in enabling (i) multi-material printing and (ii) non-destructive integrated X-ray imaging of polymer parts with microscale features.

Two-photon lithography is a laser-based direct write process for additive manufacturing of polymer parts with submicron building blocks [1–5]. In this technique, the physical mechanism of writing is the localized polymerization that occurs due to two-photon absorption [6–11]. Two-photon absorption is a nonlinear optical absorption process that occurs at high light intensities on the order of $\sim 1\ \mathrm{TW/cm^2}$ [11,12]. Such high light intensities can be achieved in the interior of a photopolymer material by focusing a femtosecond pulsed laser beam into a small diffraction-limited spot. As polymerization proceeds to an appreciable extent only in a fraction of the illuminated region, submicron printed features smaller than the diffraction-limited spot can be obtained in TPL. Complex 3D structures can be generated by scanning the printed 3D point (“voxel”) in space as illustrated in Fig. 1. This technique has been extensively used in the past to fabricate 3D structures for applications such as photonic crystals [3], mechanical metamaterials [13], microfluidics [14], miniature optics [15], and flexible electronics [16]. The functionality of these structures can be significantly increased by printing heterogeneous structures with multiple materials.

Heterogeneous structures with multiple materials are difficult to print during TPL due to the photo-polymerization based mechanism that converts a liquid resin into a solid part. This mechanism precludes one from simultaneously printing with multiple materials. Nevertheless, heterogeneous structures can be fabricated sequentially in several steps by printing (and developing) with only one material at a time. As TPL equipment is often based on retrofitted microscopes, they lack precise registration capabilities. Thus, one must visually measure

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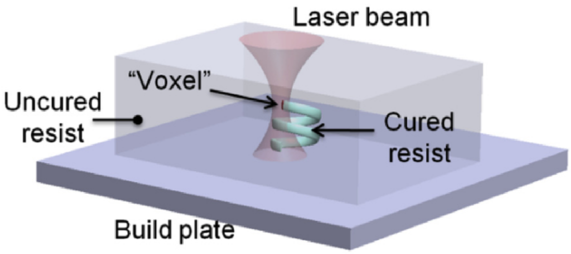

Fig. 1. Schematic of the two-photon lithography process.

the misalignments to align the features to each other during these intermediate steps [17]. To eliminate this slow and error-prone registration process, we have designed, built, and tested precise passive fixtures based on kinematic couplings so that the features can be printed directly on top of the fixtures. As these couplings register to the printer with accuracy better than ± 1.7 µm, features from the different steps can be registered to each other within less than 4 µm. In addition, these fixtures also allow for precise registration to an X-ray computed tomography (CT) system for non-destructive 3D inspection. Thus, one may print with one material, image on the X-ray system and then print with a different material. As such, these fixtures enable multi-material printing and non-destructive part inspection that is integrated with the fabrication process.

2. Design of kinematic fixtures

Kinematic couplings provide a low-cost means to passively align and register two parts to each other with submicron accuracy. Within the context of manufacturing systems, kinematic alignment schemes have been used in the past for precise registration in semiconductor manufacturing [18], optics alignment [19], and automotive assembly [20]. In contrast to other registration techniques, the relative position of the mating parts in a kinematic coupling is fully determined by the location of the finite number of contact points between the two parts. This determinism results in couplings with superior submicron repeatability. However, the primary limitation of these couplings is their relatively low load bearing capacity due to the finite number of contact points between mating surfaces. Fortunately, low load capacity of the couplings is not a major hindrance here because of the relatively low loads (< 100 mN) encountered during TPL printing and imaging. Thus, kinematic couplings are ideally suited for passive registration of features during TPL.

2.1. Material handling scheme

Our material handling scheme that uses the kinematic fixtures is illustrated in Fig. 2. In this scheme, the workpiece is mounted on a workpiece fixture that is itself mounted onto the fabrication and inspection/metrology tools through intermediate machine-specific fixtures. The same workpiece fixture can be moved across the two systems and registered to them so that direct manipulation of the workpiece is not necessary during sequential fabrication or inspection process steps. Here, we have used the commercially available Nanoscribe GT 3D printer as the fabrication tool and the commercially available Zeiss UltraXRM-L200 NanoCT X-ray imaging system as the inspection tool. The intermediate machine-specific fixtures that are used for workpiece holding in the two systems are shown in Fig. 3. The intermediate fixture for the 3D printing systems is in the form of a tray that slides into the Nanoscribe system (Fig. 3(a)) and registers to the system through a pin-slot mechanism (not shown here). The intermediate fixture for the X-ray CT system is in the form of a vertical post mounted on a plate (Fig. 3(c)) and registers to CT system through kinematic couplings (not shown here). In this work, we have not modified the registration mechanisms between the intermediate fixtures and the two systems; these mechanisms were part of the original commercial systems and cannot be readily altered. Instead, we have designed kinematic coupling based workpiece holding fixtures so that the workpiece can be indirectly handled via these fixtures. Our kinematic workpiece fixtures replace the ad-hoc workpiece holding mechanism based on adhesive tapes that is predominantly used today for these systems. Use of adhesive tape makes it impossible to passively achieve the fine alignments that are necessary for multi-material printing via sequential process steps.

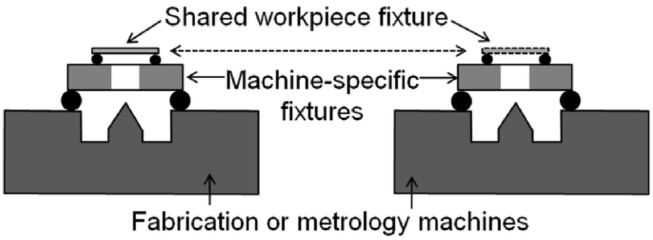

Fig. 2. Material handling scheme wherein the same workpiece fixture can be registered to multiple machines through intermediate machine-specific fixtures. In our scheme, kinematic couplings are used to register the workpiece fixture to the intermediate machine-specific fixtures.

We have designed our workpiece holding kinematic couplings (Fig. 3(b)) so that the top half of the coupling, i.e., the detachable build plate, can be registered to both the TPL printer and the X-ray imaging system. The bottom halves of the couplings (fixed base in Fig. 3(b)) are rigidly attached to the two intermediate holders (shown in Fig. 3(a) and (c)). Our kinematic couplings enable one to combine several printing and X-ray imaging steps in any desired order by (i) directly printing on top of the build plate (with or without an additional substrate) and (ii) handling the build plate instead of handling the printed part. During material handling, the bottom fixed bases stay registered to the 3D printer and X-ray imaging systems through machine-specific intermediate fixtures, whereas the top plate holder may be moved from one system to the other. In each system, the combination of top plate and fixed base forms a kinematic coupling. The capability of multi-material 3D printing is enabled by the repeatability of the kinematic couplings when the build plate is repeatedly attached to and detached from the same fixed base on the Nanoscribe fixture. Tight integration of the inspection process with the fabrication process is enabled by the interchangeability of the two halves of the couplings when the build plate is repeatedly attached to and detached from two different fixed bases.

2.2. Design of kinematic couplings

Kinematic couplings that precisely register to the two systems must (i) satisfy the space constraints for both systems, (ii) have sufficient preload so that they do not detach prematurely, and (iii) have sufficiently large factor of safety with the expected loads. Here, we briefly describe the design process and demonstrate how our couplings satisfy all these requirements.

Each kinematic coupling comprises a set of three smooth ruby-doped sapphire (Al_2O_3) half-balls that mate with three grooves through exactly six contact points (Fig. 3). Each groove is formed by a pair of smooth 52100 bearing steel precision gage pins such that the six contact points between the cylindrical pins and the balls are the only physical contacts between the two halves of the coupling. The half-balls were rigidly attached to the movable top build plate (top half of coupling), whereas the gage pins were rigidly attached to the two bottom halves. Preload in the coupling was achieved through permanent magnets attached to the bottom half that hold the ferromagnetic top plate without contacting it. We have selected a kinematic coupling design wherein half-balls mate with cylinders because of the relative