High Precision Assembly and Metrology of X-ray Foil Optics

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1. INTRODUCTION

Achieving arcsecond angular resolution in a grazing-incidence foil-optic x-ray telescope (such as the segmented mirror approach being considered for the NASA Constellation-X mission) requires accurate placement of thousands of individual foils. We have developed a method for assembling large numbers of nested, segmented foil optics with sub-\( \mu \)m accuracy using lithographically defined and etched silicon alignment microstructures, called microcombs (Fig. 1). A system of assembly tooling incorporating the silicon microstructures, called an assembly truss, is used to position the foils that are then bonded to an engineered flight structure. The advantage of this procedure is that the flight structure has relaxed tolerance requirements while the high accuracy assembly tooling can be reused.

2. MICROCOMB DESIGN

Our high accuracy alignment technique is enabled by silicon microcombs that are etched from a silicon wafer using microelectromechanical systems (MEMS) technology.\textsuperscript{1} They offer two distinct advantages over other techniques for mounting segmented foil optics. First, our fabrication technique provides the sub-\( \mu \)m accuracy which is a general characteristic of the lithographic process used in the MEMS industry, allowing for highly accurate foil placement. Second, it is possible to make intricate structures such as the leaf springs on the spring microcombs and the precisely round reference surfaces of the reference microcomb.

2.1. Design requirements

Many of the requirements of the microcombs design relate directly to the properties of the foil optics being mounted, particularly edge roughness, thickness variation, and figure errors. The baseline for the Constellation-X/SXT design is to use epoxy replication with a glass substrate. Because the edges of the foil are generally rough compared to interior surfaces, the mounting point should ideally be a small distance away from the edge so that contact can be made with the smooth mirror surface. The alignment bars of previous generation had no provision to mount the foils with a contact point other than the edge.

Replicated foils have typical thickness variations of 20 \( \mu \)m, which is due mostly to the glass substrates. Conventional spacer techniques would therefore lead to large placement errors. Even the novel “stack-up and grind” assembly method considered for the High Energy Focusing Telescope (HEFT)\textsuperscript{2} has an accuracy limited to a few microns. To accommodate the thickness variations, we use micromachined leaf springs that force the foil against the reference surface of the reference microcomb (Fig. 2).
2.2. Leaf spring design

We have developed a simple description of the mechanical requirements of the spring microcombs leaf spring that is used to optimize its dimensions. The foil optics will generally have figure errors where the shape of the foil differs from the ideal, so that the foil will have to be distorted to make contact with the reference microcomb. The leaf springs are designed so that for the expected range of thickness variation, enough force is applied to the foil to move it into place, overcoming frictional forces and the effects of figure errors in the foils.

Our analysis, based on analytic and finite element calculations, allows us to search all possible leaf spring geometries (parameterized by spring length and thickness) to minimize internal stresses given the substrate mounting requirements. The minimum load $F_{\text{min}}$ is the force required to force a foil into its desired shape. The leaf spring displacement must accommodate not only an “equilibrium” displacement, $\delta^* = \delta^* (F_{\text{min}})$, but also the maximum foil-to-foil thickness variation $\delta_{\text{max}}$. Knowing both $F_{\text{min}}$ and $\delta_{\text{max}}$, we can design the leaf spring such that the maximum stress encountered, when applying to it a displacement $\delta = \delta^* + \delta_{\text{max}}$, remains below an allowable stress level, defined as $\sigma_A = 300$ MPa, inferior to the nominal breaking strength of silicon, $\sigma_{\text{max}} = 566$ MPa.

An analytical analysis of the leaf spring, modeled as a flexible cantilever, is used to generate, for each stress $\sigma$ input, a corresponding leaf spring length $l$ vs width $h$ curve. For $\sigma = \sigma_A$, the most compact design is $l = 2.5$ mm and $h = 0.26$ mm (Fig. 1). Subsequent finite-element modeling refined these values to $l = 3.5$ mm and $h = 0.35$ mm.

3. PLACEMENT ACCURACY TESTS

Direct measurements of the dimensions of the microcombs using a microscope and precision translation stage have shown that the microcombs are fabricated to a higher tolerance than the 2 $\mu$m resolution of the measurement. To more accurately characterize microcombs, we have designed a series of experiments that uses our breadboard test assembly system to specifically measure the alignment capabilities of the microcombs.
Figure 2. Foils are referenced by the spring microcombs against the reference microcombs which in turn are referenced against a flat reference surface. All the references are made by point contacts as illustrated in the top view of a foil being clipped in between a reference tooth and a spring tooth.

The system has a rectilinear geometry and is designed to mount a nest of parallel foil optics. Since we are currently not able to manufacture foils with accuracy comparable to the alignment accuracy of the microcombs, we instead used rigid flat plates. The plates are 102×102×2.3 mm$^3$ fused silica and are held inside the assembly truss using three spring-reference microcomb pairs (Fig. 3). The tests are designed to measure the parallelism of a plate mounted in different “slots” of the assembly truss. A microcomb slot is the space between one reference tooth and its corresponding spring tooth. Angles are measured with an autocollimator which reads out $\mu$rad in pitch and yaw with a resolution of 0.1 $\mu$rad.

The repeatability of mounting of a plate in a given slot was measured by a repeated process of sliding a rigid flat plate against the reference microcomb teeth in a given slot, measuring its angle, then removing it. Results of repeatability tests show a typical 1 $\sigma$ mounting repeatability error of about 0.11 $\mu$m in both axes. To measure mounting variations between slots, the plate was installed in several different slots and for each slot, five measurements were made. Variation between slots corresponds to a 1 $\sigma$ slot-to-slot mounting error of less than 0.5 $\mu$m in both pitch and yaw. To measure alignment between the mounted plate and the reference flat (Fig. 2), the angle of the plate and reference flat were compared with the plate mounted in several different slots. Results of reference flat measurements, corrected to only show errors due to the microcombs, shows a mounting accuracy standard deviation of 0.3 $\mu$m in pitch and 0.4 $\mu$m in yaw. This result is encouraging. It suggests that the reference between the microcombs and reference flat is as good as the reference between the microcombs and the rigid plate, both being accurate to about 0.5 $\mu$m.

Another series of experiments has addressed the impact of the spring microcomb on the alignment capacity. It has consistently shown that the force applied by the spring microcomb (Fig. 3) affects the placement accuracy. In fact, the error introduced is quasi-linear with respect to the leaf spring displacement and therefore with respect to the force. The maximum error is about 0.7 $\mu$m and is obtained when the leaf bottoms out, i.e. when the force is $\sim$-0.36 N.

It is hypothesized that the distortion of the contact interface between the reference microcomb and the foil is due to contact stresses. Contact stresses occur when curved surfaces of two bodies are pressed together by external loads. The Hertz theory provides a useful set
of equations for the contact stresses between surfaces with only one radius of curvature each which allowed us to confirm our hypothesis.³

On the one hand, since the main component of the forces applied to the foils during the assembly process can be predicted, we can take their effect into account while designing the reference microcombs. On the other hand, some effects such as friction or thickness variation cannot be predicted and therefore could introduce errors. For example, the effect of the thickness variation of the substrate would lead to an error between the placement of the thicker and the thinner substrates of about 0.26 \( \mu m \).

4. CONCLUSION

We have described the requirements and design process of the microcombs used inside an assembly truss to provide subarcsecond foil placement. Tests performed thus far have demonstrated that the alignment system can mount rigid flat plates with a positioning tolerance typically better than 0.5 \( \mu m \), resulting in a high degree of parallelism that for the Constellation-X design would correspond to a \( \sim 1 \) arcsecond resolution. These tests have also underlined the effects of Hertzian contact stresses on the placement accuracy.

REFERENCES