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Precision cutting and polishing of thin metal substrates with electroless nickel plating for bent neutron-focusing optics

Tran Thi Hong Trang[1]
[1] *Faculty of Fundamental Science, Hanoi University of Industry, 298 Cau Dien, Bac Tu Liem, Hanoi, Vietnam*

Abstract—*Neutron supermirror is a metallic multilayer that enables achromatic reflection of slow neutrons, which are becoming increasingly important for material analysis. This paper reports a fabrication of a thin metal substrate for the deposition of the neutron supermirror, which is intended to be utilized as a bent focusing mirror. The substrate is an aluminum plate covered with an electroless nickel plating, planarized by diamond cutting on a vacuum chuck and smoothened by polishing using colloidal silica. The fabricated substrate has a form deviation of approximately 16 µm, which needs improvement. The surface roughness was below 0.12 nm (rms), well qualified for the supermirror deposition.*

Keywords— *Ultraprecision Machining, Polishing, Electroless Nickel Plating, Bent Mirrors, Focusing Mirrors, Neutron Optics.*

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I. INTRODUCTION

Structural analysis of materials using neutron beams are becoming increasingly important, not only in academia but also in industries, because the neutrons provide valuable information of materials with their unique characteristics such as the high sensitivity to light elements and the deep penetration into surfaces. For better utilization of neutron beams, neutron optics are necessary for efficient guiding and focusing of the neutrons onto the samples. Neutron supermirrors —a metallic multilayer that enables an achromatic reflection of slow neutrons— is an indispensable component in neutron optics. In this paper, we report on the development of a metal substrate for the deposition of the neutron supermirrors.

Neutron supermirrors, which are typically a multilayer of nickel and titanium, require extremely smooth surface with a roughness on the order of angstroms. This is because a rough substrate also roughens the interfaces of the multilayer, resulting in a low neutron reflectivity. For this reason, plates of float glasses whose natural surfaces satisfy this requirement, has been the primary choice for the supermirror substrates. By bending the supermirrors on such glass substrates, successful developments of elliptic and parabolic neutron-focusing mirrors have been reported [1-6]. However, the glass substrates have two problems. First, they are weak against strong irradiation; radio activated elements in glass often degrades the supermirror coating. Second, their brittleness severely limits the curvature of bending. To overcome such problems, metallic substrates have been proposed to replace the glass substrates [7, 8].

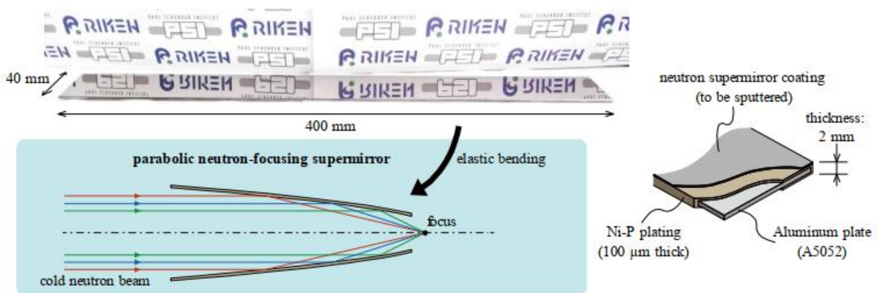

Fig. 1: Thin metal substrate with a Ni-P plating for the neutron supermirror deposition and its usage as bent parabolic neutron-focusing mirrors.

As substrates for supermirrors, the major problem for the metals is in polishing, because a sub-nanometer roughness is difficult to obtain on a metallic surface due to the grain boundaries. A solution to this problem is to use an amorphous, phosphorous-rich, electroless nickel-plating (Ni-P plating), which is a surface coating widely used for optical molds. This idea has been demonstrated by a neutron-focusing mirror, in which the Ni-P plating was applied on a figured elliptic surface [8]. In this work, we utilize the same technique to a thin substrate as shown in Fig. 1. Our intention is to utilize the metal substrates in a system of bent neutron-focusing supermirrors. Such supermirrors on metal substrates will withstand stronger irradiation and will be much easier to bend compared to those on glass substrates. Further, it may be utilized in adaptive neutron optics, in which curvatures of the mirrors are changed to fit the experimental requirements [9]. The rest of this paper details the fabrication method for the substrates, as well as the precision and the surface roughness of our first prototype.

II. PREPARATION

As shown in Fig. 1, the metal substrate in this work is strip-like, so that it can be bent into a parabolic form. The substrate is 400 mm long, 40 mm wide and 2 mm thick. The base material is an aluminum alloy A5052. We chose this material because it contains no heavy metals that are radioactivated with long half-life.

The aluminum plate was cut out from a plate 4 mm thick, which is the thinnest commercially available. We removed 1 mm from each side by milling, to avoid uneven stress. After the milling, the flatness and the parallelism was approximately 50 µm. Such precision is fair for ordinary machining but insufficient for Ni-P plating, because the error reduces the margin for the subsequent diamond machining. Thus, both sides of the aluminum plate was planarized by diamond machining, in the same way as for the Ni-P surface that is described in the next section. The prepared aluminum plate was then plated with the Ni-P, uniformly on its exterior with a thickness of 100 µm.it.

III. DIAMOND SHAPER CUTTING

We chose diamond shaper cutting as the planarization process for the Ni-P plated substrate. In the shaper cutting, a non-rotating cutting tool is fed along straight lines; after cutting a single line, the tool is shifted by a certain pitch to continue with the adjacent line, and this line-by-line cutting continues until the whole surface is cut. Note that this method is not the optimal choice for a planarization in terms of efficiency; a turning process is better suited for a planarization than the shaper cutting. However, we chose the shaper cutting for the easiness of introducing a vacuum chuck.

Fixturing is the most difficult part in machining a thin substrate. For example, when the work is fixed onto the machine while deformed by stress, it will spring back to an undesirable form when detached from the machine. For this reason, fixturing with bolts or a vise was not an option in this work. Thus, we have decided to introduce a vacuum chuck for the work fixturing. Vacuum chucks need to be connected to vacuum pumps through tubes, and the tubing is much easier with the non-rotating process such as the shaper cutting.

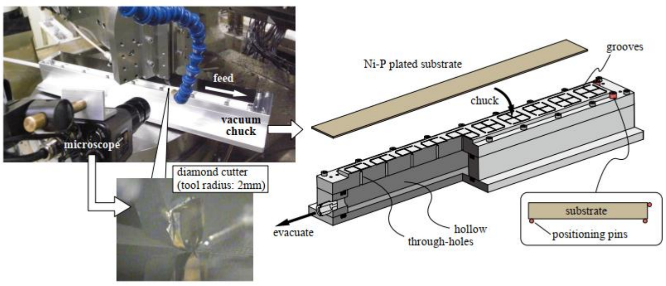

Fig. 2: Diamond shaper-cutting of a thin Ni-P plated substrate using a vacuum chuck.

We designed a vacuum chuck as shown in Fig. 2. The vacuum chuck has a hollow inside, which is evacuated at a gauge pressure of -50 kPa. The hollow is connected to the grooves on the chuck's surface via through-holes. Considering the width of the grooves, which is 1 mm, the suction force is approximately 80 N. The vacuum chuck was fixed on a 5-axis ultraprecision machine (NPIC-M200, Nagase Integrex Co. Ltd.). On the machine, the chuck's surface was shaper-cut using a diamond tool. The flatness of the surface measured on the machine using cantilever-type electric micrometer was below 1 µm. Onto this flattened surface, the Ni-P plated substrate was fixed, guided by the three positioning pins.

In the shaper cutting, we used three axes of the 5-axis machine: the tool-feeding axis (X), the tool-shifting axis (Y) and the cut-in axis (Z). The vacuum chuck was rotated around the Z-axis by 30 degrees, because the stroke of the X-axis was insufficient considering the acceleration/deceleration distance. Thus, we performed the cutting along the tilted substrate by simultaneous control of X- and Y-axis. As a cutting tool, we used a round-tip diamond cutter with a tip radius of 2mm, whose rake face was aligned perpendicularly to the feeding direction. By the shaper cutting, we removed 30 µm of the Ni-P plating from each side of the substrate. The cutting conditions were changed gradually as the cutting proceeded. For the finish cutting, the tool-shifting pitch was 0.1 mm and cut-in depth was 2 µm. The feed rate was fixed at 4 m/min for all conditions.

We removed equal amount of the Ni-P plating from both sides to avoid bimetallic thermal deformation. Figure 3 shows the effect of the bimetallic effect, through the simulation by finite element method. In this simulation, we assume a 50 mm long statically determinate beam of A5052 sandwiched by Ni-P, with only the Ni-P on the top side machined to be 70 µm thick, whereas that for the bottom side is left as plated at 100 µm. A temperature rise causes such unbalanced beam a deformation of 0.3 µm/K, because of the difference in the coefficient of thermal expansion; the coefficient is 23.5×10-6 K-1 for A5052, whereas for Ni-P it is 12×10-6 K-1. The deformation is small but significant, considering the use of the substrate as a bent mirror. For example, if the substrate is bent by multiple supports that are evenly spaced by 50 mm, a temperature depending waviness, whose amplitude changes by 0.3 µm/K, will appear on the surface. Thus, we decided to cut both sides equally to avoid such temperature dependence.

IV. POLISHING

The most important requirement for the substrate is to have a sub-nanometer surface roughness for the deposition of the neutron supermirror. To meet this requirement, we performed two-stage low pressure polishing on the diamond-machined substrate as shown in Fig. 4. In this polishing, the substrate is fixed in a supporting frame, which is also plated with the Ni-P. The substrate and the frame are then put into a tilted plastic container, in which the slurry flows constantly. At this condition, a felt disk pad with a diameter of 20 mm scans the whole surface in a raster scanning pattern, while rotating at a speed of 3000 rpm and pressed against the substrate at a pressure of 3 kPa.

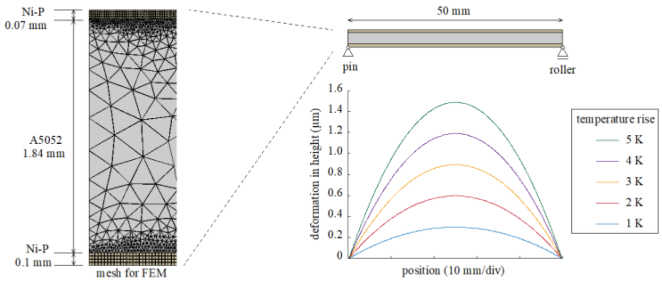

Fig. 3: Simulation result of the bimetallic thermal deformation of a Ni-P plated substrate caused by uneven plating thickness. Finite element method software used is COMSOL Multiphysics.

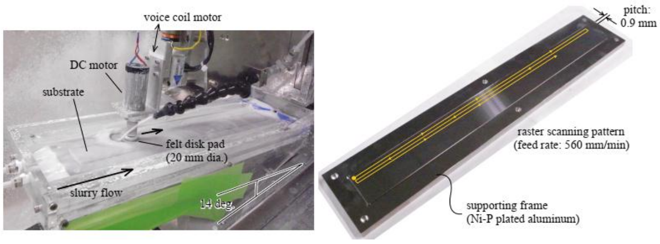

Fig. 4: Polishing of a Ni-P plated substrate in a tilted container with flowing slurry, and the raster scanning pattern of the polishing tool.

In the first stage of polishing, we used alumina slurry with a nominal particle diameter of 300 nm. This polishing removes the cutter marks on the surface, created by the diamond machining. The duration of the first stage polishing was 16 hours, and the roughness after this polishing was approximately 2 nm in root mean square. For the second stage polishing, we used colloidal silica as the slurry, whose particle size is 80 nm. This polishing took 16 hours, and the roughness was successfully reduced to sub-nanometer level, as described in the next section.

V. RESULTS: FORM DEVIATION AND SURFACE ROUGHNESS

We measured the form of the finished Ni-P plated substrate using a laser interferometer (Verifier QPZ, ZYGO) as shown in Fig. 5a. In this measurement, the substrate was fixed on the same vacuum chuck as in the diamond shaper cutting. The vacuum chuck was mounted on a linear slide. The slide was necessary because the substrate is much larger than the aperture of the interferometer, which is 4 inches in diameter. Using the slide, we measured the whole surface in 8 separate shots and stitched them together to have the complete information of the surface.

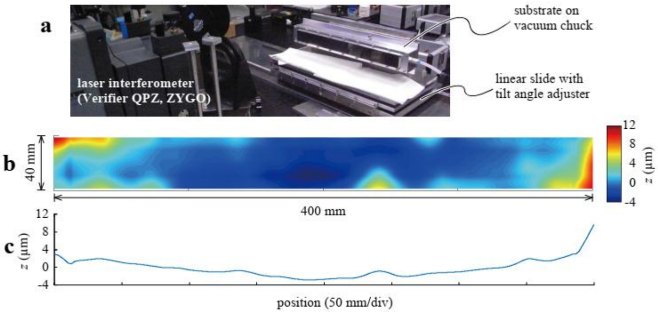

Fig. 5: Form measurement of the Ni-P plated substrate: (a) the measurement setup using laser interferometer, (b) form deviation map and (c) form deviation in cross-section along the centerline.

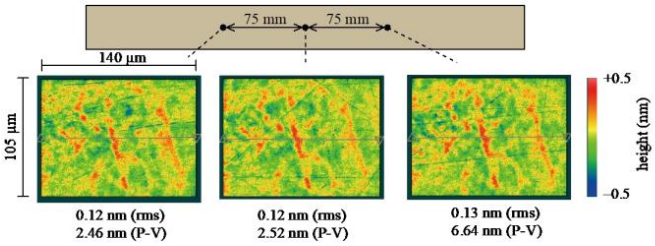

Fig. 6: Roughness of the polished Ni-P plated substrate, measured with white light interferometer (Newview 7200, ZYGO)

Figure 5b shows the map of the form deviation, and the cross section along the centerline is shown in Fig. 5c. The peak-to-valley height difference of the form was approximately 16 µm. This difference is larger than we expected, much worse compared to the flatness of the vacuum chuck measured on machine, which was below 1 µm. Since this is our first trial, we do not have enough evidence to prove the cause of this form deviation. Possible causes include dusts caught between the chuck and the substrate, an insufficiency of suction pressure, and a fluctuation of polishing pressure.

Finally, we measured the surface roughness of the substrate at three different positions using a white light interferometer (NewView 7200, ZYGO) and the results are shown in Fig. 6. Note that the height distributions in all three positions show almost identical patterns. Differences are observed only in the scratches, which originate in polishing. This indicates that these patterns are not actually present on the substrate, but are related to the reference mirror of the interferometer. Thus, all we can conclude from these data is that the roughness is immeasurably low with this interferometer.

These results show that further improvements are necessary in planarization and in measuring the surface roughness. However, considering the figure error in majority of the area is within a few microns, and the surface roughness is well below a nanometer in rms, we regard this substrate worth testing for its application as a substrate for a bent neutron-focusing supermirror.

VI. CONCLUSION

We fabricated the first Ni-P plated thin metal substrate for the bent neutron-focusing supermirror. For the planarization and the smoothing of the substrate, we applied the diamond shaper cutting and the polishing using colloidal silica, respectively. The results show that the surface roughness is satisfactory for the deposition of the neutron supermirror. However, further reduction of form deviation is necessary, which may be achieved through a corrective machining based on the measured form. Our future work is to sputter the neutron supermirror onto the substrate, construct a bent focusing mirror, and test for its neutron-focusing capability at a neutron beamline at Paul Scherrer Institut.

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