THERMAL TOLERANCE TEST FOR THE DEVELOPMENT OF A HOLLOW RETROREFLECTOR FOR FUTURE LUNAR LASER RANGING. H. Noda[1] , H. Araki[1], S. Kashima[1], S. Utsunomiya[2], S. Tsuruta[1], K. Asari[1], S. Yasuda[2], [1]National Astronomical observatory of Japan (2-21-1 Osawa, Mitaka, Tokyo 181-8588 Japan / 2-12 Hoshigaoka, Mizusawa, Oshu, Iwate 023-0861 Japan, hirotomo.noda@nao.ac.jp), [2]Japan Aerospace Exploration Agency (Tsukuba, Ibaraki, Japan).

Introduction: The distance between the Moon and the Earth can be accurately measured by transmitting a laser from a telescope on Earth to laser retroreflectors that were placed on the lunar surface by the US Apollo missions and Soviet Luna missions and observing the reflected photons, thereby allowing for investigation of lunar rotational variations. This experiment, called Lunar Laser Ranging (LLR), started in 1970's and has been conducted for almost 45 years for the elucidation of the lunar interior and development of the lunar precise ephemeris (e.g. [1]).

Due to the time difference between the two ends of reflector arrays generated by optical libration of the Moon, the level of precision has hitherto been limited for determining small variations in the process of energy dissipation in the lunar interior. As part of Japanese SELENE-2 lander, which is under study, a proposal has been made to set up a new single reflector mirror in the southern hemisphere away from the reflectors already in place, allowing for high-precision measurement of lunar rotational variation. The development of the future LLR retroreflector is conducted by several groups, among which solid ([2]) or hollow ([3]) retroreflectors are studied individually. We are developing 'single aperture and hollow' retroreflector mainly because the solid retroreflector, or corner cube prism, has the upper limit of aperture due to the inhomogeneity of fused silica as the prism material. We are aiming at 20 cm diameter hollow reflector, which meets the requirement of the future observation: one-order higher ranging accuracy can be expected and the amount of light is equivalent to, or more than the most productive corner cube prism array at Apollo 15 site ([4]).

So far, material selection and mirror-forming methods have been investigated for the fabrication in terms of thermal, structural and optical performance. As a result of simulation, monocrystalline silicon was selected as the best candidate material. On the other hand, three-plane bonding and single-piece manufacturing were parallel studied as methods of forming the hollow mirror. In three-plane bonding, the critical issues are minimal distortion during the bonding process and lasting stability after bonding. It turned out that optical contact bonding, which was considered as preferred candidate, requires a curing temperature of more than 800 °C to improve the bonding strength. Therefore we conducted an experiment to heat the small pieces of Si to clarify how the hardness of the optical contact bonding improves with respect to the applied heat, and at the same time, to measure the surface accuracy and roughness of the mirror surface after heating which might affect the optical responses.

Experimental setup: We conducted two experiments. i) First, mirror-polished (<1 nm in rms surface roughness) Si samples with the dimension of 20 mm x 21 mm x 5 mm were prepared for the test whether the heating affects the surface of the plane mirror. Before the heat test, the surface accuracy and surface roughness were measured with a laser interferometer (ZYGO, GPI XP) and an Atomic Force Microscope (AFM; Digital Instruments Nanoscope). The same measurements were done after the heating for comparison. Note that the area measured with AFM is 1 micron by 1 micron for each sample, while the position accuracy of AFM is about 1 mm, therefore it is not the case that the same region was measured before and after the heating. ii) For the test of stability of optical contact force, five sets of optically-contacted Si pieces of the same dimension were prepared so that one of the three planes could be pushed with a tensile tester (Shimazu, Autograph AG-1) and as a result shear stress could be applied in the bonding planes (Fig. 1). Each sample had been pre-heated to 200 °C during the optical contacting process. Both samples of i) and ii) were heated in the same electric furnace up to 100, 400, 600, 800, 1000 °C for one hour, and they were naturally-cooled down until the temperature became room temperature within half or one day. For the test ii), samples were put in a box which held the whole bonding structure. One side of the box is transparent and can be observed while the force is applied.

Results: *Surface accuracy and roughness:* The measurement results of the laser interferometer for the surface accuracy and of AFM for the surface roughness are summarized in Table 1. The rms of the surface accuracy becomes worse after heating only in the case of 800 °C exposure. However, the amount of deterioration is small (0.004 to 0.007 lambda, where the wavelength is 633 nm), and the value after the heating is comparable to other cases. Therefore we may conclude that the heating to Si samples does not affect the surface accuracy. On the other hand, the surface roughness measured with AFM became worse by about 10 to 40 percent after the heating, except in the case of 1000 °C exposure. In general, the low-scatter optical base plates have a few (e.g. 2 nm) Ra values, and these results have the same level of Ra, where Ra stands for arithmetic average of absolute value. Although we need to carry out the scatter light simulation in the future, the values of surface roughness measurement might not cause significant light scatter.

Change of surface color of 1000 °C *sample:* The surface color turned to more bluish than one before heating. Other samples does not show such changes of color. It might be caused by heat oxidation process on the surface, which is often used for the stabilization of the silicon wafer. The oxidant surface does not seem to affect the surface property, or rather, seems to contribute to the improvement of the surface roughness.

Shear strength test of Optical contact bonding: The maximum fracture strength was measured for optically-contacted samples which experienced 100, 400, 600, 800 °C exposure. The sample of 1000 °C exposure was not broken even with the maximum force which the device could apply, therefore the lower limit of the applied force was recorded. The result is shown in Fig. 2. As was expected, the samples which experienced higher exposure temperature have higher fracture strength.

Summary and future works: In the heating experiment, one which experienced 1000 °C exposure showed the best performance in terms of surface accuracy, surface roughness, and fracture strength. Therefore it is expected that the optical contact bonding of two planes with curing temperature of 1000 °C can be used for manufacturing the large-aperture single mirror. However, stability of the angle between two bonding planes, called dihedral angle, is the most important for the optical performance. Even if accuracy of 0.1 seconds of arc is achieved before heating, it is not clear now whether the dihedral angle keeps stable after heating. We plan to perform this test in the near future.

References: [1] Williams, J. G. et al. (2001) *JGR, 106*, 27933–27968. [2] Currie D. et al. (2011) *Acta Astron., 68*, 667–680. [3] Turyshev S. et al. (2013) *Exp. Astron., 36,* 105-135. [4] Otsubo et al. (2011) *Earth, Planets, and Space, 8,* e13–e16.

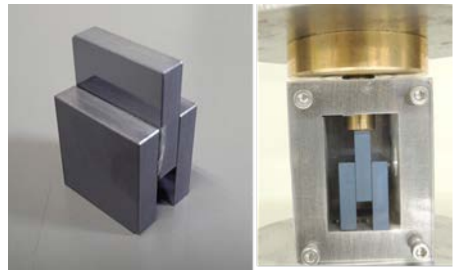

Fig. 1 A test piece for shear stress test of optical contact bonding (left). The dimension of each plane is 20 mm x 21 mm x 5 mm, and three planes are optically contacted each other. One plane in the middle is shifted and bonded so that forces can be applied to this part to measure the maximum fracture strength between optically contacted planes (right).

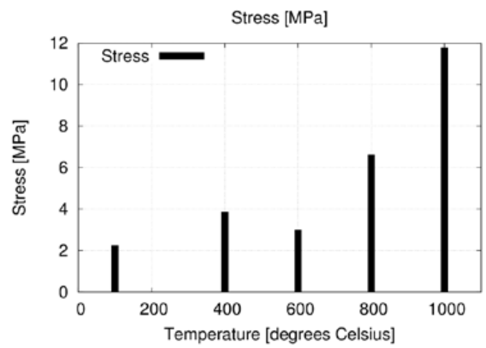

Fig.2 Exposed temperature vs fracture strength in MPa unit in the optical contact bonding test. Because the sample in 1000 °C was not broken, the value is lower limit.

Table 1. Result of surface accuracy and roughness measurement. rms is root mean square, and Ra stands for the arithmetic average of absolute value of height.

Temperature [deg C]	Surface accuracy ZYGO interferometer [rms in (633nm)]		Surface roughness AFM [Ra]	
	before	after	before	after
100	0.007	0.007	0.096	0.104
400	0.006	0.006	0.099	0.111
600	0.006	0.006	0.105	0.127
800	0.004	0.007	0.164	0.233
1000	0.010	0.009	0.322	0.225