Measurement & Minimization of Mount Induced Strain on Double Crystal Monochromator Crystals.

J. Kelly, S. G. Alcock

Diamond Light Source, Harwell Science & Innovation Campus, Didcot, UK, OX11 ODE

E-mail: jon.kelly@diamond.ac.uk

Abstract. Opto-mechanical mounts can cause significant distortions to monochromator crystals and mirrors if not designed or implemented carefully. A slope measuring profiler, the Diamond-NOM [1], was used to measure the change in tangential slope as a function of crystal clamping configuration and load. A three point mount was found to exhibit the lowest surface distortion (< 2µrad peak-to-valley) over the whole length of the monochromator 2nd crystal. A thermal circuit, comprising the liquid nitrogen manifold to the crystal, was modelled using experimental data for the 2nd crystal absorbed beam power and braid link thermal conductance. In the case of the I09 monochromator 2nd crystal assembly, the temperature drop across the 3 indium mount pads was calculated to be 25% of the total 0.22 K. Less than 1% loss of flux due to the 2nd crystal strain is expected at 25keV. This three pad mount will be used in the monochromators on the I09 and I23 beamlines at Diamond Light Source.

1. Introduction

Synchrotron facilities such as The Diamond Light Source (DLS) Ltd are designed to produce intense beams of light for scientific investigation. High power densities generated by insertion devices necessitates the use of cryogenic cooling for double crystal monochromator (DCM) optics. Typically, a liquid nitrogen (LN2) cryocooler is used as the heat pump, with various schemes for interfacing the wetted area of the LN2 manifold with the diffracting crystal surface. The DLS in-house designed DCMs use a 1st crystal clamped between two copper (Cu), LN2 manifolds, with the 2nd crystal cooled by conduction via three Cu foil stacks from the 1st crystal manifold. The 2nd crystal is clamped onto a Cu plate with an indium foil interstitial layer. An image of the assembly fitted with 6 clamps is shown in Figure 1. The 2nd crystal was not side cooled as the incident heat load is small and symmetrical cooling would have been difficult to achieve with the flexible cooling links.

We investigate the effect of the clamp load on the external shape of the crystal surface, and then infer similar distortions within the crystals. The mechanical force imparted by the clamps, secures the crystal during rotation and thermal cycling, and ensures sufficient heat transfer. Only a light clamping force i.e. less than the yield stress of indium 1.3 MPa [3], is required to provide a stable mount, but the heat transfer coefficient increases with pressure in this range. The 1st crystal employs a side cooled geometry which allows the clamping pressure to be raised above the yield stress of indium. In this case, the heat transfer depends more upon area rather than pressure [2]. The tangential surface of the crystals was measured using the Diamond-NOM [1], a non-contact profiler capable of measuring the surface topography of optical assemblies with sub-nanometer resolution and repeatability.
Figure 1: Diamond Light Source DCM 2nd crystal assembly. The Si(111) crystal is clamped onto the indirectly cooled Cu mount plate by up to six clamps. A 0.5mm thick, indium interstitial layer is used to improve heat transfer. The crystal is 38 x 25 x 135 mm. The assembly was installed with three clamps located above the three indium pads. This arrangement repeatably caused the lowest surface distortion and hence lowest crystal plane distortion.

2. Experimental technique

Prior to the clamping tests, the tangential slope of the crystal was measured in two configurations: supported on a flat surface; and by two half-cylinders at the Bessel points. No significant difference was observed between the data sets, indicating that the crystal aspect ratio (length versus cross sectional area) was sufficient to neglect gravitational distortions. This “background” form of the unclamped crystal was subtracted from all subsequent scans of mounted crystals to reveal the change in shape caused by the mounting process. Assuming that the internal crystal planes are not distorted in the unmounted state, the aim is to minimize the change in the shape as the crystals are clamped. The crystal, indium foil and the Cu mount plate were assembled with PEEK plastic clamps to apply load using a stack of Bellville washers, under M4 bolt heads. Spring washers provide a method for selecting the force and making the clamps relatively insensitive to differential thermal contraction. At room temperature and < 10 MPa PEEK exhibits negligible creep. Bolts were tightened through one full revolution to give 100 N/bolt ± 20 %. The accuracy of the force was estimated from results of an earlier load cell study. 100 N was chosen from previous experience mounting similar crystals. Thirty three tests were performed to investigate the effect of load, indium thickness, indium pad size, location and history. For clarity, selected data sets are presented in subsequent sections.

3. Results and discussion

3.1. Crystal clamping stabilisation time

Diamond-NOM tests quickly revealed that optical slope changed with time, indicating that the indium foil takes time to flow, relieving the applied clamping stress.

Figure 2: Crystal slope evolution with time. The sequential scans take 6 minutes each. The 1st scan was taken approximately 6 minutes after the clamping was applied. 6 clamps applied a total of ~ 500 N. This shows that care should be taken to let the assembly reach equilibrium prior to measuring the slope.
Five sequential scans (see Figure 2) were captured over a 30 minute period. The reduction of crystal distortion with time suggests that in this case, the crystal elasticity is providing the indium yield stress. This test was repeated without changing the preload, to prove that this effect is not due to thermal stabilisation post handling.

3.2. 2nd Crystal Slope Repeatability & Indium History
The yield stress of pure indium at room temperature is 1.3 MPa [3], so a greater local stress must be applied under the clamps to cause macroscopic plastic deformation. A minimum force of 8.5 kN is required to raise the indium above the yield stress over the whole crystal mount surface. Indium will flow until the local stress drops below the yield threshold.

The clamped crystal distortion depends upon; 1) Flatness of the base of the Si crystal and Cu mount plate, 2) Flatness, and hence history, of the indium foil, 3) Clamping force, tightening sequence, and duration, 4) Location of clamping force.

The manufactured flatness and roughness of the Si and Cu was constant throughout the series of tests. The indium sheet has an unknown form: a combination of the manufactured profile, deformations caused during assembly, and plastic deformations of the current and previous clamping. As a consequence, the crystal distortions using a single indium sheet were not reproducible, and significant crystal deformation in the tangential direction was observed far below the bulk yield stress of indium (see Figure 3, Single Sheet Curves). Three indium pads (10 x 30 mm) under the clamp points was the only mounting configuration tested which repeatedly gave slope changes of < 2 µrad peak-to-valley (PV). The pads decoupled the crystal form from the Cu mount plate, and ensured the high stress points were beneath the clamps and hence did not create a bending moment. It was postulated that thinner (0.1 mm) indium foil might give a reduced slope change because the local deformation under the clamps would be less than for the 0.5mm foil. However, tests with the 0.1 mm foil revealed a larger slope change. This effect could be attributed to a reduced ability to compensate for the Cu and Si form, or a larger variation in the foil form when installed (the thin foil was very difficult to handle without creating folds and creases). Results of the different clamping tests are summarized in Figure 3. The unclamped relaxed state illustrates the noise level of a single measurement, and the repeatability of the technique. The wide range data was taken with a single sheet of indium and 6 clamps at 100 N. Low clamping load data sets illustrate the improvement observed with a 3 pad mount. The point at which the curves cross, correspond to the off-centre location of the central clamp.

**Figure 3:** Crystal slope data for 4 test configurations and an example of FEA data which assumed an additional single sheet of indium with a 0.01% of indium’s Young’s modulus to simulate roughness. A large crystal plane slope change can cause an inhomogeneous monochromated beam due to the variation of angle across the beam foot print. The worst case is at high energy when the foot print is elongated and the rocking curve is narrow e.g. at 25 keV 11.1 µrad rocking curve width over a 12 mm foot print.
3.3. Finite Element Analysis
A simple FEA study was performed using ANSYS 12.1, to see if it was possible to reproduce the experimental data. In the model, the Si was bonded to a constrained indium sheet, allowing the indium to squeeze out from under the Si crystal, rather than unrealistically restraining the bottom surface. Applying 3 x 100 N clamping loads in the FEA model caused negligible distortion because the indium was assumed to be a perfectly flat sheet. It is not practical to model realistic contours or texture, as the required mesh size would be prohibitively small. Instead, a second layer with a reduced Young’s modulus was added to simulate the indium texture. Assuming a Young’s Modulus value of 0.01% of the bulk gives good qualitative agreement with the experimental data. We conclude that crystal distortion could be reduced if the indium foil were uniformly flattened prior to clamping. In practice, this is difficult to achieve as the indium adheres to surfaces when under pressure.

3.4. 2nd Crystal Slope Effect on Flux Transmission
The clamping distortions change the local angle of X-ray incidence along the length of the crystal, causing a misalignment of the 1st and 2nd crystal Darwin widths and reducing X-ray transmission. Assuming the Darwin width to be a rectangular distribution, a misalignment of 1% of the rocking curve width will cause a 1% transmission loss. As the DCM scans from 2.1 keV to 25 keV the beam footprint moves along the crystal, increasing in length from 1 mm to 13 mm. The Darwin width reduces as the energy increases, so the crystal distortion has a greater effect. Assuming that the 2nd crystal is adjusted to maximize the flux as the energy is scanned, the high load curve (Figure 3, Single Sheet 6 x 100N) would cause a 5% loss in transmission; whereas the other data sets would cause less than 1% loss. This estimate is neglecting any 1st crystal thermal distortion. Flux loss is not significant for this Si(111) crystal set but will become severe for higher order reflections and smaller d spacing crystal cuts.

3.5. Thermal Analysis
The thermal circuit from the liquid nitrogen manifold at crystal 1 to the beam footprint on crystal 2 was mathematically modelled. Experimental values were used for the Si-In-Cu [4] and the flexible cooling link interface conductances (Thermal link DLS study). Of the expected 32 W beam power incident on the 1st crystal, 0.17% is reflected on to the 2nd crystal. This percentage was measured on the I20 monochromator at DLS using a similar geometry. The temperature drop across the 3 indium mount pads was calculated to be a 25% of the total 0.22°C, for the I09 DCM. The flexible cooling link is the limiting component in the cooling circuit accounting for 60% of the total temperature drop.

4. Conclusion
The three indium pad 2nd crystal mount has been used within the DLS DCM, as it causes minimal strain with sufficient heat transfer for the application. The FEA comparison suggested that developing a method to flatten the indium prior to assembly would reduce the clamping induced crystal distortion. Full power tests on the beamlines will provide the definitive evidence for the crystal mount method.

References
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