High Performance Supermirrors on Metallic Substrates

C. Schanzer¹, P. Böni¹, and M. Schneider¹²

¹ SwissNeutronics, Bruehlstrasse 28, CH-5313 Klingnau, Switzerland
² Laboratory for Neutron Scattering ETH & PSI, CH-5232 Villigen PSI, Switzerland

E-mail: christian.schanzer@swissneutronics.ch

Abstract. Recently, we have developed an optimized process for polishing Al substrates leading to an extraordinary low surface roughness comparable to float glass of high quality. Indeed, supermirror coatings with \( R = 91\% \) at the critical angle of reflection of \( m = 2 \) were produced demonstrating the excellent quality of the Al surface. Supermirror coated Al substrates open new options for advanced neutron optical devices. As one example neutron guides can start very close from the moderator. We investigated this option by Monte-Carlo simulations for i) a conventional, curved guide and ii) an elliptic guide. In case of i) an increase of flux at long wavelengths is obtained because of complete illumination of the phase space accepted by the guide. The elliptic guide starting close to the moderator (ii) has significantly enhanced neutron transport properties since only useful neutrons are extracted and transported to the sample. As a result such a guide concept is superior in terms of flux when compared with a conventional guide system and in terms of signal to background and well defined beam focusing compared with an elliptic guide starting at a larger distance from the moderator. In particular, experiments on novel materials, which are often only available in small quantities or samples under extreme conditions will profit from neutron beams of such high quality.

1. Introduction

The recent years have demonstrated that almost all modern neutron scattering instruments rely on the efficient transport of neutrons by means of neutron guides. Present neutron guides are usually assembled from flat glass substrates. The natural surface of floated glass provides an extremely small roughness enabling for high reflectivity even for very large angles of reflection, i.e. up to \( m = 6 \) times the critical angle of Ni. For example, reflectivities \( R > 80\% \) for \( m = 4 \) and \( R > 70\% \) for \( m = 5 \) are regularly obtained [1].

Unfortunately, glass has limited stability against irradiation, temperature, and mechanical stress, effects which are particularly severe close to the moderator. Therefore neutron guides can only be used for distances larger than approximately 1.5 m from the moderator causing under illumination of the phase space of the guide with increasing wavelength. In order to improve the illumination some guide systems have reflectors at their front end, which are assembled from polished metal plates. In the case of steel mirrors [2] the phase space of the reflector is smaller than the neutron guides accept, thus the illumination of the guides is still incomplete. Supermirror coated, polished aluminum assemblies [3] still suffer from low reflectivity of typically \( R = 60\% \) at \( m = 2 \) due to a poor surface roughness. Alternative replica techniques for neutron mirrors on metallic substrates are mostly applied to simple Ni mirrors [4] because the supermirrors lack in terms of reflectivity [5]. Moreover, advanced optics, e.g. elliptic guides, require high \( m \) supermirrors at their entrance to fully exploit their performance.
Recent developments in neutron supermirrors [1, 6] enable for excellent reflectivities, but require atomically smooth substrates. Hence metal substrates of a similarly high quality are desired for demanding applications, which are discussed here.

2. Supermirror coatings on metallic substrates

For the application of metallic substrates it is desirable to use similar formats as it is common for glass based guides. Therefore the format of 250 mm $\times$ 130 mm $\times$ 10 mm was selected and aluminium as the material to avoid severe activation by neutrons in the long term. On such substrates the processes to refine the surface were steadily developed and the results were monitored by atomic force microscopy (AFM) on a scan area of 10 $\mu$m $\times$ 10 $\mu$m, similar to the in-plane coherence length of the neutrons. Floated glass served as the reference since, either non-borated or borated, it has been proven to be the best substrate for supermirror coatings when prepared properly. Fig. 1a shows a typical image of the topography of a float glass. The analysis results in a RMS roughness of $\sigma_{RMS} \approx 1.8$ Å. Fig. 1b depicts the AFM image of the aluminium surface as it is obtained from the present state of the art of the refinement process. A roughness of $\sigma_{RMS} \approx 2.0$ Å is obtained, which is rather close to the typical value for floated glass. Measurements on various locations confirm the homogeneity of the quality indicating that the refinement process is constant across the complete substrate area.

![AFM images of the surface of a) float glass and b) aluminum substrate. The surface of the aluminum exhibits fine scratches from the polishing. The color code is identical for both images. The measurements are performed with the AFM easyScans 2 from Nanosurf.](image)

Finally, the substrate was coated with a Ni/Ti supermirror $m = 2$. The measured reflectivity profile is presented in Fig. 2 showing $R = 91$ % at $m = 2.1$. For comparison the reflectivity of a similar supermirror on float glass is included in Fig. 2 reaching $R = 94$ % at the edge of the supermirror. The excellent neutron reflectivity of the supermirror on the aluminium substrate confirms the excellent smooth surface. However, it becomes also clear that the float glass is still slightly superior to the refined aluminium substrate, which is in good agreement with the trend seen from the AFM data. The absolute roughness values $\sigma_{RMS}$ may not be real because of the finite lateral size of the AFM tip, which results in a smoothed measured profile.

![Neutron reflectivity of a $m_{\text{nominal}} = 2$ supermirror on a refined aluminum substrate (diamonds) and on float glass (squares). The $m$-value is slightly larger than the targeted value due to a small deviation of the thickness calibration of the deposition process.](image)
3. Applications – a Monte Carlo study

3.1. Conventional, parallel guide

The conventional neutron guide NL1 of the cold guide system at the FRM II is considered for a comparison of various designs for the transport of cold neutrons. NL1 has a constant aperture of 60 mm × 120 mm, a length of 36 m and starts about 2 m from the moderator. Geometrical details, flux measurements and simulations of the actual guide are presented in [3]. For the present simulations the initial section of NL1 is extended towards the moderator starting at a distance of 0.1 m.

Fig. 3 plots the gain which is obtained by the extended guide starting closer at the moderator compared to the presently installed guide. The plot shows two distinct ranges with a cross over at a wavelength of about 5 Å. Below that the extension of the guide does not improve the transmission since the size of the moderator is large enough to provide complete illumination of the phase space accepted by the actual guide. The incomplete illumination for larger wavelengths is eliminated when the guide starts close to the moderator resulting in an increasing gain with increasing wavelength.

3.2. Elliptic guide

In [7] an elliptic guide is compared with other guide concepts, in particular with the existing conventional guide that delivers the neutrons of the Swiss Spallation Neutron Source (SINQ) to the instrument TASP. As a result, the elliptic guide was shown to be the superior guide concept. For the present study, we used the same parameters for the elliptic guide as in [7], however, we extended it at the entrance towards the moderator, while maintaining the long and short axis of the ellipses. Hence the entrance has a reduced cross-section of 15.85 mm × 54.38 mm starting at a distance $d = 0.3$ m to the moderator, compared to the original aperture of 35 mm × 120 mm at $d = 1.5$ m.

Fig. 4 compares the gain factors of the original and extended elliptic guides with respect to the conventional guide, identically computed like in [7]. The original elliptic guide shows the largest gain in terms of flux of about 5 in the range of $3 < \lambda < 6$ Å. For an identical coating of $m = 3$ the extension of the guide leads to a reduced gain factor of about 2.4 in the respective range. This is understood since the smaller entrance reduces the number of neutrons which are collected from the finite size of the moderator and can propagate via multiple reflections to the sample (10 mm × 40 mm).

The reduced gain of the extended elliptic guide can be partially recovered by utilizing supermirrors with $m = 4$. Those allow larger reflection angles, especially at the ends of the elliptic guide, thus increasing the phase space accepted at the entrance and focused at the end of the guide.

In addition to the transmission properties, issues of the radiation background shall be discussed. A part of the background depends on the size of the opening in the biological shielding of the source, which is essentially determined by the cross-section at the entrance of the guide. As an indicator for signal/background the ratio of transmitted flux normalized to the entrance cross-section is computed.
Fig. 4 shows that the extended elliptic guides have a gain in signal/area of guide entrance more than one order of magnitude, thus making them superior in terms of signal/background.

![Comparison of the gain factor of various elliptic guides with respect to a conventional guide.](figure)

4. Conclusion

Metallic substrates are envisaged for neutrons optics in order to overcome limitations implied by glass. Benefits are: i) increased durability against large changes in temperature and intense irradiation, ii) enhanced mechanical deformation possible to impose more complicated geometrical designs of guides, for example for focusing, and iii) robustness against mechanical damages and implosions.

In this paper we present a breakthrough in the refinement of the surface of aluminum substrates enabling for a supermirror reflectivity \( R = 91 \% \) at \( m = 2.1 \). The low roughness is confirmed by AFM measurements and it is almost identical to float glass. Hence, even supermirrors with excellent reflectivity at larger \( m \)-values appear feasible and are the goal of future developments.

Dedicated applications of neutron guides with metallic substrates are initial guides very close to the moderator. Here we demonstrate by simulations that an enormous gain is obtained for a conventional guide that starts close to the moderator, e.g. 30 % at a wavelength of 15 Å. For the concept of an elliptic guide, the extension towards the moderator provides an improved transport of neutrons. While the transmission is moderately reduced, significant improvements in the signal-to-background ratio can be obtained. Moreover the point-to-point transformation can be more closely approximated thus reducing chromatic aberration and providing a “clean” beam with well defined, compact phase space.

Acknowledgement: Work was supported by the Swiss National Science Foundation through the National Centre of Competence in Research MaNEP.

References

[1] www.swissneutronics.ch
[2] S.J. Cho, private communication
[3] K. Zeitelhack, C. Schanzer, A. Kastenmüller, A. Röhrmoser, C. Daniel, J. Franke, E. Gutsiedl, V. Kudryashov, D. Maier, D. Päthe, W. Petry, T. Schöffel, K. Schreckenbach, A. Urban and U. Wildgruber, Nuclear Instruments and Methods in Physics Research A 560 (2006) 444
[4] F. Lang, Metallic guide using replica technics, ILL guide workshop (2006)
[5] Yuji Kawabata, Masatoshi Suzuki, Seiji Tasaki, Kazumasa Somemiya, Nuclear Instruments and Methods in Physics Research A 420 (1999) 213
[6] M. Hino et al., Nuclear Instruments and Methods in Physics Research A 529 (2004) 54
[7] C. Schanzer, P. Böni, U. Filges, T. Hils, Nuclear Instruments and Methods in Physics Research A 529 (2004) 63.