Development of All-Aluminium Mirrors for Imaging Cherenkov Telescopes

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Abstract

The production and properties of light weight all-aluminium mirror elements for imaging Cherenkov telescopes with a tessellated mirror is described. The mirror elements have a sandwich-like structure with built-in heating. The reflecting surface is obtained by diamond machining the mirror front aluminium plate, which is afterwards anodically protected with an Al_2O_3 layer.

1. Introduction

The observation of gamma ray sources above 200 GeV, and thus the beginning of proper gamma ray astronomy in the Very High Energy (VHE) domain, became only possible with the advent of large area Imaging Atmospheric Cherenkov Telescopes (IACTs). They consist of a large area segmented reflector, focussing the Cherenkov light from VHE air showers onto a pixelized camera of a few degree diameter field of view.

The mirror elements on the majority of current IACTs are based on aluminized glass. They are formed by a glass layer of around $1 - 2$ cm thick with a spherical shape, obtained either by the slumping technique − see for example (Loh, 1993) − or by mechanical grinding. The reflecting surface is created by evaporating a thin layer of pure Aluminium (Al 99.99%) onto the glass surface. The delicate Al surface is normally protected by an additional layer of SiO_2 vacuum deposited or electrolytically grown Al_2O_3.

The current trend in VHE gamma ray astronomy is to build IACTs with higher sensitivity (see contributions to this conference) by using larger mirror dishes and/or finer granularity camera. This puts new demands on mirror production such as better optical quality, lower weight and reduced prices. In this context, the production of glass mirrors, although a mature technology, has some limitations:

- Limitation in weight reduction while conserving optical precision.
- Difficulties to produce mirrors of slightly different focal lengths in a cost effective way.
- Need of high vacuum equipment for both Al and protective surface deposition.

In the following, we describe the production and features of a new type of all-aluminium mirrors for future IACTs. They are designed to overcome some of the above mentioned drawbacks of glass mirrors and allow one to add some new features, such as integral heating to avoid dew or frost deposition. Also, easy production of aspherical mirrors or post-production cutting is possible.

This paper is structured as follows: In section **2** we detail the mechanical construction of the mirrors, while section **3** is devoted to the production of the reflecting surface. In section **4**, several tests on anodic coating are described. Finally, in section **5** the conclusions and an outlook for future improvements are given.

2. Mirror Structure

A mirror element is comprised of a thick (5 – 8 mm) *Al* alloy plate and an HEXCELL supporting panel. *Fig.* 1 shows an exploded view of such an element, formed by an $AlMgSi0.5$ plate, glued onto a sandwich formed by two 1 mm *Al* plates enclosing a 20 mm HEXCELL layer.

The HEXCELL outer circumference is filled with a low density Epoxy compound ($\rho = 0.6$ g/cm^3, filled with microspheres), acting both as a stiffening frame and as a seal. The need of *Al* HEXCELL instead of a much cheaper plastic honeycomb spacer is dictated by the requirement of good heat conductivity. In a zig-zag groove on the top 1 mm *Al* plate a heating wire is embedded in order to heat the mirror to prevent dew or frost. The heating power of each mirror element is ~ 20 Watt ($\Delta T < 1.5°$ over the mirror), with an emergency peak power of 100 Watt/m^2 for deicing.

The prefabricated sandwich plate is glued to the *Al* front plate at room temperature taking care to avoid any mechanical stress. This is needed in order to prevent distortions in the spherical shape during the diamond turning procedure.

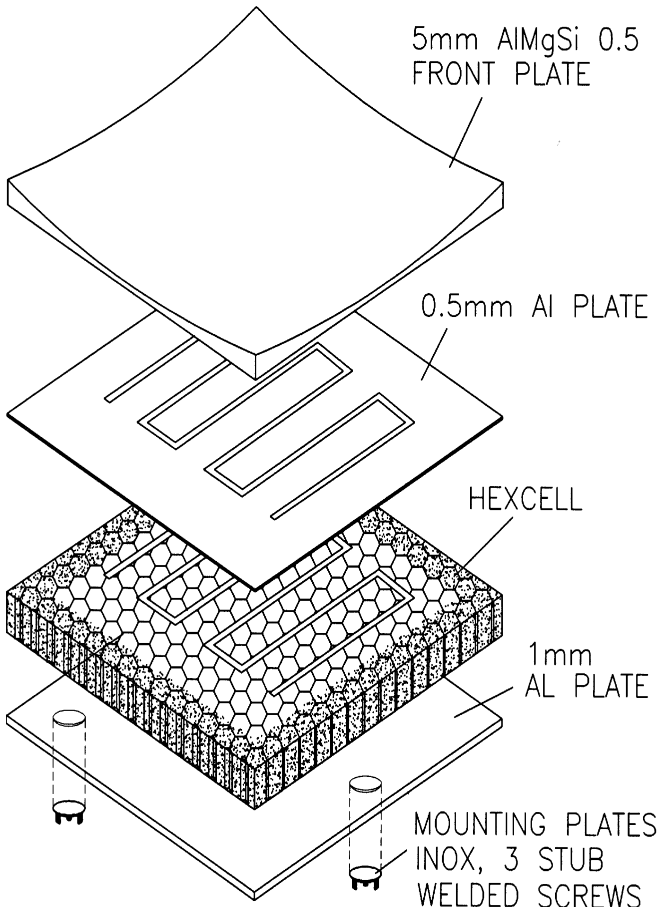

Fig. 1: *Exploded view of a mirror element.*

Currently we have finished the production of 30 prototype mirrors with hexagonal shape and focal distance $f = 490$ cm to substitute current mirrors on HEGRA CT1 telescope. We have produced as well 8 prototype mirrors with rectangular shape and $f = 1700$ cm for the MAGIC telescope (see contribution to this conference).

3. Production of the Reflecting Surface

The reflecting surface is produced by computer-controlled diamond turning the mirror aluminium front plate. The resulting surface is then coated to protect it against environmental hazards.

3.1. Diamond Turning Technique

The milling procedure itself comprises two steps. In the first one, the plate, of a thickness around 5 mm, is milled on an ordinary numerically controlled machine down to about the correct spherical shape within 0.1 mm of the final curvature and a thickness of 1.6 mm in the centre.

In a second step, the final reflecting surface is produced on a high precision, computer controlled lathe with a diamond head fly cutter. The lathe is made by a large diameter air bearing rotary table, onto which the mirror blanket is fixed. The fly cutter, also mounted on an air bearing spindle, is equipped with a diamond pre-cutter that removes about $5 - 8$ μm, while the final cut removes about 1 μm of the aluminium. The approximate time needed to complete this second step is about two hours.

During this procedure, some steps have to be carefully controlled in order not to spoil the quality of the reflecting surface. For example, due to the low weight and modest stiffness of the mirror element, it has to be carefully fixed onto the heavy mass rotary table in order to avoid small vibrations during the turning procedure. Also, the mirror blanket has to be mounted free of stress, or else the surface will deform after releasing.

With this technique, surface roughness of about 0.01 μm can be obtained. Also, for the mirrors produced in this way for HEGRA CT1 telescope, we have measure mirror angular resolutions as good as 0.02°.

Regarding surface reflectivity, we have compared the results obtained with this technique with the ones from some other standard mirror production techniques. As can be seen in *Fig.* 2, the diamond turned mirror (MPI Al bulk) show similar reflectivities as traditional evaporated pure Al mirrors ($AlMg4$ 99.99), all above 85% for $\lambda > 300$ nm. Silver mirrors have reflectivities of 98% for $\lambda > 500$ nm. However, its strong drop below $\lambda = 350$ nm would seriously compromise IACT observations at low zenith angles.

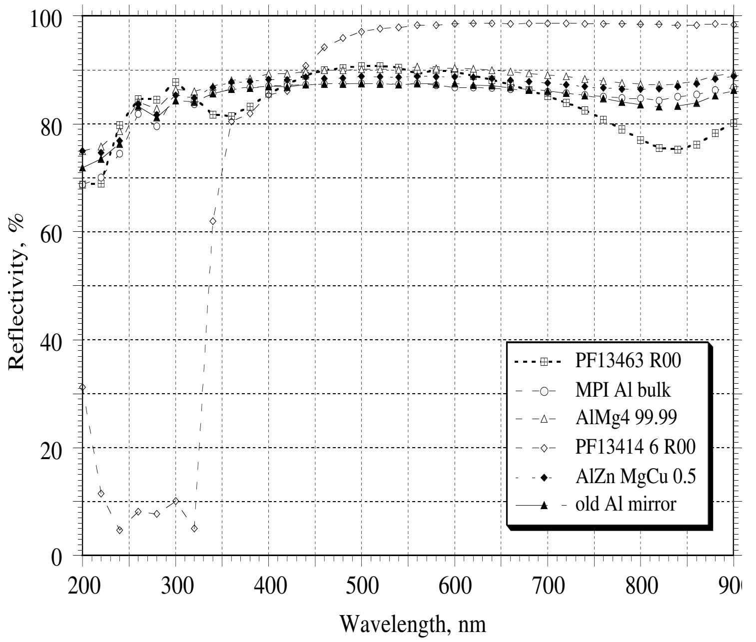

Fig. 2: Reflectivities for several mirror types.

While retaining the good optical properties of glass mirrors, as shown above, computer-controlled diamond turning technique allows easy modification of the surface curvature in a mirror by mirror basis. In this way, one can readily produce mirrors with slightly different radius of curvature to match the overall parabolic profile of a reflector as needed for the MAGIC telescope.

The diamond machining of the mirror has been developed together with two companies, Kugler and L-Tec, and carried out in their factories.

3.2. Choice of the Reflecting Surface Alloy

The type of Al alloy chosen for the mirror surface requires the compromise among a series of sometimes contradicting conditions:

- The alloy must be hard enough to allow diamond machining. This can be only achieved by Al alloys including a moderate component of impurities, among which Mg is the most favoured, while Fe, Pb, Cu, Mn and Zn are highly disfavoured.
- The alloy production method has to guarantee a minimal crystalline structure, which is only obtained in forged materials.
- The material should be basically stress free, as mainly achieved in cast alloys.
- Finally, the Al alloy should be of outstanding anodisation quality[1] to allow the growth of an anodic coating both hard and transparent. This required the exclusion of certain impurities (like Fe or Cu), Mg and Si being the most favoured. Also, the remaining impurities must be uniformly distributed, as obtained in forged materials.

In view of above requirement, the required Al alloy should contain no admixture of heavy metals like Fe, Cu, Zn or Pb. But such material is very difficult to obtain and normally Fe and Cu impurities tend to increase the alloy hardness.

Moreover, big Al plates cut from forged blocks (to avoid crystalline structure) are very difficult to obtain. Also, these plates have to be further tempered at elevated temperatures for internal stress release.

Originally, we started the mirror production with the $AlMg4.5Mn$ alloy because of its excellent properties for diamond turning and good anodisation quality. But recently we have switched to the $AlMgSi1$ alloy, which is also well suited for the diamond turning technique, and shows better results

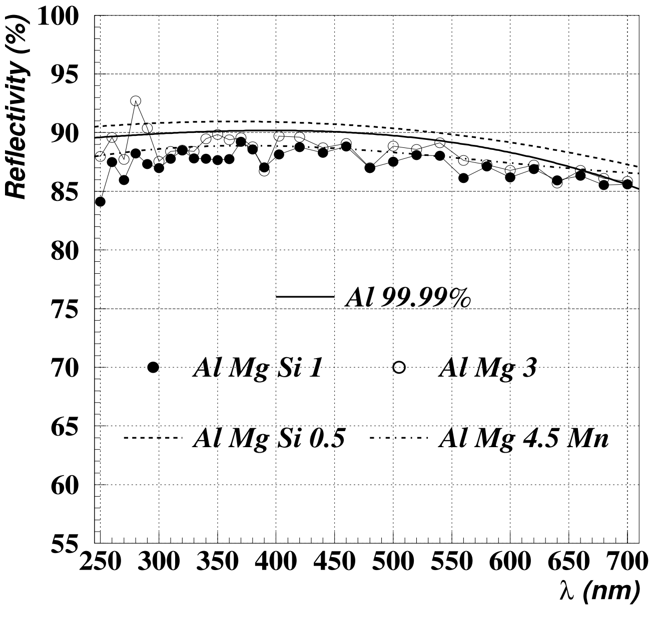

Fig. 3: Reflectivities for different aluminium alloys diamond polished.

[1]Standard anodisation quality, as required in industrial corrosion-protected equipment, does not normally lead to hard transparent coatings.

after anodising. This fact is confirmed by a smoother Al_2O_3 surface and a slight enhancement in the reflectivity after coating, as shown in *Fig.* 5.

In this respect, the $AlMgSi0.5$ alloy seems to be nearly optimum, as shown in *Fig.* 3 and *Fig.* 5, but for the moment is not available in large plates, as required for our mirrors. *Fig* 3 shows the reflectivities obtained by diamond polishing different Al alloys, where one can see that, in general, all alloys tested give similar figures as pure Al.

3.3. Surface Protection

The machined aluminium surface is rather soft and can be chemically attacked in outdoor exposure. This problem is more critical than for mirrors in astronomical telescopes because IACTs have in general no protecting dome. Also, simple cleaning procedures to remove dust or grease from the mirror surface will immediately damage it.

Therefore, the mirror has to be protected by a hard, chemically inert film. The film should be transparent between at least 300 to 700 nm (where Cherenkov radiation has a sizeable intensity) and interference losses in this range should be minimal. To meet these requirements, we have initially considered three coating materials:

- SiO_2, vacuum deposited
- Al_2O_3, grown via anodical oxidation
- CVD[2] diamond coating

CVD diamond coating shows, on small samples, good transparency and extraordinary hardness and wear resistance. Unfortunately, prices are rather high and the technology required to coat large areas is still in a development phase. These two facts make this coating unpractical.

The technology of SiO_2 coating is well under control and particularly suited for Al evaporated onto glass substrates, where sealing of pin holes and transition edges between Al and the glass are of great importance. The reflectivities of mirrors coated with SiO_2 are above 85% in the 300–600 nm wavelength range (see *Fig.* 5), but its hardness is moderate. Furthermore, this technique requires high vacuum and evaporation or sputtering equipment, which makes it expensive.

We have chosen for our mirrors the Al_2O_3 anodic coating for its simplicity, cheapness, and good reflectivity and wear resistance. In the next section, we will described the procedure we have used to perform this coating and their figures for different material we have tested, also in comparison with some other coatings.

4. Anodic Coating

In this section we will describe the procedure and results we have obtained when coating different mirror surfaces with an Al_2O_3 film via anodic oxidation. This procedure follows closely the one originally described in Hass (1949) and has been already applied to mirrors for several

[2]CVD stands for Chemical Vacuum Deposition

IACTs or fluoresces detectors (Harris et al., 1992; Loh, 1993; Cresti, 1996). In all these cases the surface to be anodised was evaporated pure Al onto a glass substrate. This fact already poses some differences with respect to our mirrors: The thinness of the evaporated Al layer ($\sim 1\mu$m) does not allow high currents to be applied during the electrolytic anodisation. Also, Al alloys usually show worse behaviour under anodisation than pure Al.

4.1. Procedure

In order to coat the mirror, this one is made the anode in an electrolytic cell. As cathode any conducting material could be used as the electrochemical reaction taking place in it does not liberate any metallic cations to the solution. In our case we used a thin plate of high purity aluminium with the same geometrical shape as the mirrors to be coated.

Concerning the electrolyte for the anodic oxidation, two different types can be used, that result in different properties of the coating. On the one hand, acid solutions that dissolve, to a certain extent, the Al_2O_3 layer while it is being formed, like sulphuric or oxalic acid. In this case, the oxide layer produced has a substantial thickness ($\sim 10\mu$m) and is composed by a thin underlying amorphous Al_2O_3 layer covered by a thick Al_2O_3 porous layer. This is the type of coating used to protect Al construction materials for outdoor purposes in which high specular reflectivity is not needed. However, recently some companies have refined the technique, producing rolled Al material with reflectivity of the order of 90%, aiming to equip commercial lamp reflectors.

On the other hand, boric acid solutions or acidified organic ammonium salts do not dissolve the Al_2O_3. In this way, a hard transparent amorphous oxide layer is formed, the so-called barrier-type layer, with thicknesses around 100 nm.

In our case, the electrolyte used consists of a 3% tartaric acid solution which is brought to a pH range between 5.0 and 5.5 by adding ammonia. Finally, we added a 3% of ethylene glycol to keep the solution stable.

Under above conditions it has been shown for evaporated Al over glass substrate (Harris et al., 1992), that after a few minutes, a hard barrier-type layer is formed. This layer has a thickness d proportional to the voltage applied to the electrolytic cell ($d \simeq 1.4$ nm/V), independently of the current flow.

For the mirrors we have produced, the procedure had to be modified because we were using an Al alloy. The main reasons are the alloy production method and its impurity content. Concerning the first item, wrought alloys are better anodised than cast alloys, due to the fact that in the former, impurities are distributed in a more homogeneous way. Concerning the second item, a higher fraction of impurities in the alloy worsens the quality of the anodic coating.

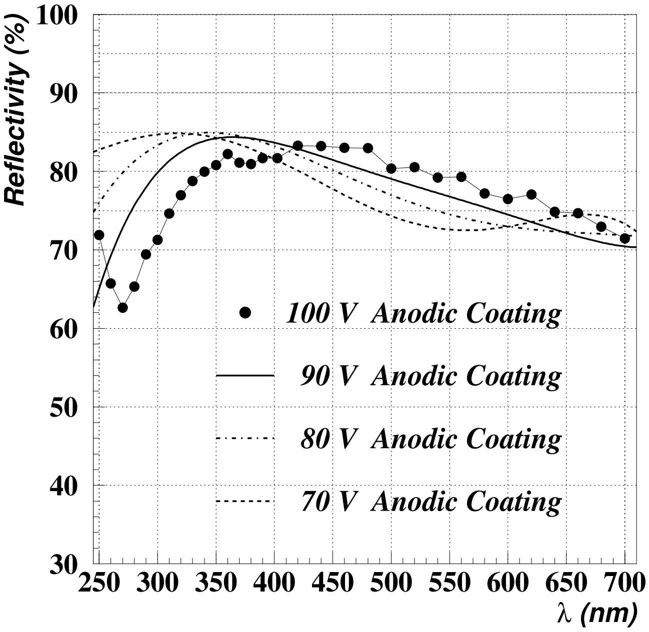

Fig. 4: Reflectivities after anodising $AlMg4.5Mn$ diamond turned mirrors with different voltages.

Also the kind of impurity plays a role, Mg, $MgMn$ and $MgSi$ being the most common favoured alloys, while those containing Fe or Cu impurities are not adequate for anodisation.

4.2. Results

The first result to be quoted is that, independently of the fact that our mirrors are formed by an Al alloy instead of pure Al, we readily found a proportionality between voltage and oxide thickness, as can be seen in *Fig.* 4. Each coating, simply obtained by varying the applied voltage, shows a reflectivity curve with the typical interference minima and maxima, depending only on the oxide film thickness d. As can also be seen in the figure, an applied voltage of 90 V produces a coating thickness with the highest reflectivity in range of interest (300 nm $< \lambda <$ 600 nm). Therefore this is the voltage setting we have used to anodise the new HEGRA CT1 mirrors.

For comparison, we have anodised a diamond turned sample mirror with pure Al evaporated on top of an Al alloy substrate. The reflectivity obtained for this coating shows the typical interference pattern, as compared to the pure Al uncoated reflectivity (*Fig.* 5)

We have tested several alloys, among those well suited for diamond polishing, in order to find the one giving the best coating (in terms of reflectivity and wear resistance).

At first, we have tested the alloy $AlMg4.5Mn$, for which we found that the conditions used for evaporated pure Al were not suitable, as some porous layer was grown on top of the barrier-type layer, compromising the reflectivity figures. During the tests we found that the faster the layer grew the smoother the oxide surface was, so we settled of a current density $i \simeq 30$ mA/cm^2 resulting in an anodising time of ~15 s. In order to further smoothen the oxide surface, we sank the mirror in an oxidising solution (H_2O_2 30%, 24 h). With this method, the mirror showed a modest increase in reflectivity, and the microscopic surface structure looked in fact smoother than before the treatment. When compared to anodised pure Al, $AlMg4.5Mn$ coating showed an expected drop in reflectivity of around 5% (see *Fig.* 5).

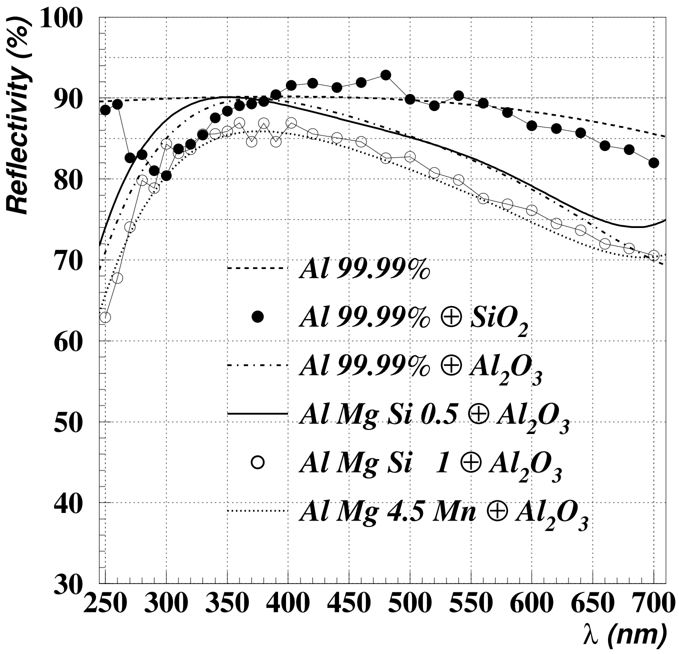

Fig. 5: *Reflectivities of different coatings, compared with Al 99.99% uncoated reflectivity.*

We have also tested some other alloy types ($AlMg$ and $AlMgSi$), among which the best one turned up to be $AlMgSi0.5$. In *Fig.* 5, one can see that the reflectivity for this alloy coating matches anodised pure Al, even without any treatment to smoothen the oxide coating.

Finally, *Fig.* 5 also shows as a reference the reflectivity of a sample mirror obtained by evaporating pure Al onto an Al alloy substrate, and coating it with SiO_2. Note that this reflectivity curve can be misleading in the sense that the oxide film is around 40% thicker, producing the reflectivity maxima displaced to the right.

4.3. Ageing Tests

We have also performed some preliminary ageing tests. At first, we placed an $AlMg4.5Mn$ anodised sample outdoors for two months under the harsh weather conditions provided by the Munich winter. We observed a drop in reflectivity of around 2% for the coated surface, and a slightly larger one for the uncoated sample. Nevertheless, this drop is within the measuring precision of our reflectometer, so more tests will be needed to obtain a clear answer.

We also treated some coated samples with $NaOH$ (2.5%, 1 min). We found that mainly all tested coated surfaces were moderately attacked, except anodised pure Al and $AlMgSi0.5$ alloy and the sample coated with SiO_2, which remained nearly unaltered. We also found that, surprisingly, uncoated $AlMgSi0.5$ suffered hardly no attack, while the other uncoated materials showed the expected strong corrosion.

Finally we performed some very simple abrasion test showing similar results on both anodised and SiO_2 coated surfaces, but quantitative results are not yet available.

5. Conclusions and Outlook

We have developed a standard technique to produce a new type of all-aluminium diamond turned mirrors. They show several advantages over classical glass mirrors:

- Light weight, being 50% lighter than glass mirrors.
- No risk of breaking.
- Allowance of built-in heating.
- Cost effective production of different focal lengths with high precision.
- Less expensive, provided the anodisation technique gives adequate long term stability.
- The absence of the aluminium $-$ glass interface makes these mirrors less prone to defects in case of corrosive attacks.
- A careful choice of the alloy used for the reflecting surface allows anodic overcoating with optical properties matching classical glass mirrors.

Some of these advantages might be decisive when applied to forthcoming large area IACTs, either in single dishes or in telescope arrays.

We have recently finished the production of thirty such mirrors to replace current glass mirrors of HEGRA CT1 telescope. In this way we will test reliably both above mentioned features and ageing behaviour over the next years.

6. Acknowledgements

We would like to thank M. Cresti, E. Loh, K. Harris and C. Raubenheimer for providing us with very useful information concerning the anodisation procedure. Moreover, the help from H.J. Gebauer and the MPI – München workshops staff for the anodisation of the new HEGRA CT1 mirrors has been invaluable. We are also indebted to many colleagues from the MAGIC design group for many critical discussions and useful suggestions.

This work is partly supported by the german BMBF and the European Union TMR program under grant ERBFMBICT960991.

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