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Advanced Lightweight Mirrors for Space-Based Missions

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ABSTRACT

With more rapid, affordable access to space and the availability of large-volume fairings, owners and users of current and future space-based optical systems are desiring large-aperture or segmented aperture primary mirrors for their missions. This in turn is driving demand for new approaches to produce the optical components and/or mirror segments more cost-efficiently and with faster manufacturing lead times than traditional optical components. Harris is executing a mirror development strategy called Advanced Mirror Construction (AMC) to meet this need while still meeting the challenging requirements of space-based optics. A key component of this strategy is the utilization of replication to produce precision lightweight mirror components. In this paper, we present the motivation and initial results for the replication of lightweight, ultra-stable mirrors and mirror segments as well as the other key elements of the AMC strategy.

INTRODUCTION

Today when a space-based imaging capability need is identified, it may take four or more years and high cost to gain that capability. However, current space resiliency requirements are creating a strong need for much more rapid deployment of precision imaging capabilities. New strategies and approaches for producing high-quality optical components are needed to reduce system schedule, weight, and cost.

Many solutions to achieve this are currently being pursued and have been pursued in the past, and it is common that they do not make it to full implementation. Very often, the reason is one or more of the following: 1) the real market need or problem was misunderstood, 2) the schedule, weight, and cost drivers for current precision mirror production are misunderstood, 3) the implementation risk of new solutions is underestimated, or 4) the business implementation aspect of the technology was not considered.

Harris has performed a study into the schedule and cost drivers of large, precision mirror production, a risk assessment of potential enabling technologies and materials, and an assessment of business implementation. Through this evaluation, we have developed a mirror strategy called Advanced Mirror Construction (AMC) that targets the key schedule, weight, and cost drivers for mirror production by leveraging several key technical and business enablers. AMC places Harris on a new mirror optimization curve that delivers not only near-term schedule and cost reductions, but also significant schedule, weight, and cost advantages for future mirror architectures.

There are three key initiatives under the AMC strategy:

- Capture range replication
- Mirror structure and materials optimization
- Advanced component joining

The AMC strategy includes the three key initiatives with varying extent and risk/ reward profiles. The need, strategy, and current solutions under the AMC strategy are shown in Figure 1.

Resiliency: Shorter cycle time/higher production rate
Persistence: Higher quantity or larger apertures at higher production rate, lower cost, lower mass
Flexible Mission Architecture: Lower mass
Relieve Acquisition Constraints: Material diversity, shorter mirror development timeline

Capture Range Replication (CRR): Replication to within capture range of final finishing

Mirror Structure: Advanced materials; simple components; fast, rapid construction

Advanced Bonding: Stable, versatile

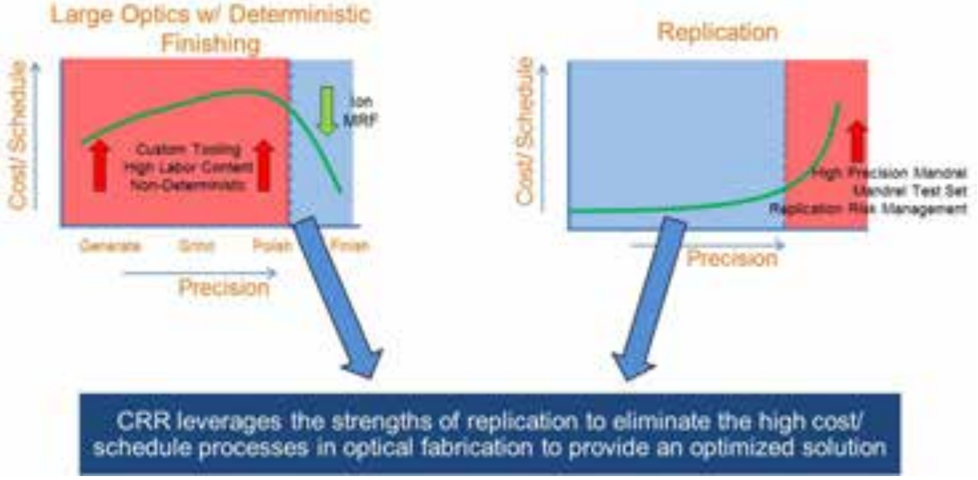
Figure 1: Advanced Mirror Construction (AMC) Strategy

ADVANCED MIRROR CONSTRUCTION TECHNOLOGIES

The AMC mirror strategy consist of multiple mirror solutions with varying risk versus reward profiles.

Capture Range Replication Description

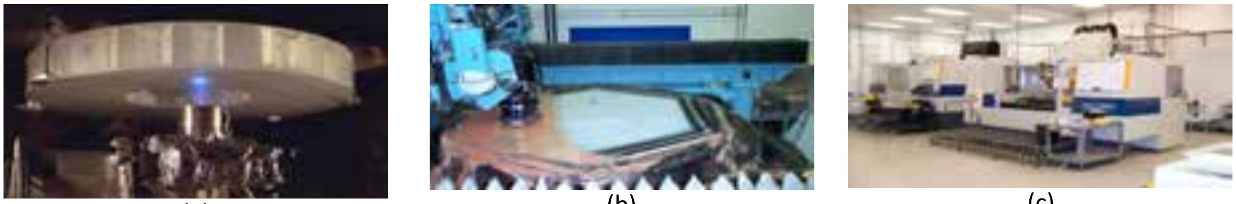
One of the key capability strategies under AMC is Capture Range Replication (CRR). CRR is a replication process that replicates a mirror or mirror faceplate within capture range of final deterministic finishing, such as ion figuring[1], magneto-rheological finishing (MRF^{TM})[2], computer controlled, small tool polishing[3]. Through this process, we avoid both the long schedules and high costs associated with generating, grinding, and pre-polishing of traditional optics, as well as the lengthy schedules and high cost of precision replication.



CRR leverages the strengths of replication to eliminate the high cost/ schedule processes in optical fabrication to provide an optimized solution

Figure 2: Capture Range Replication (CRR) description

Manufacturers attempting to leverage replication to achieve final optical specifications may find that the technical challenges, costs, and schedule time lines grow quickly due to: 1) the need for a high-quality mandrel that must be better than the final mirror, 2) the need for a custom test set for the mandrel that must have lower uncertainty that a traditional mirror test set, and 3) replication risk management, which will drive the complexity of the replication rig. Most research and development attempts to achieve direct replication of optical tolerances on large, lightweight optics over the past 50 years have run into these challenges and, as a result, were unable to fully implement the strategy. Using CRR with existing, proven final finishing technologies provides an optimized replication solution that Harris has implemented successfully.



(a) (b) (c)

Figure 3: Deterministic finishing processes: a) ion figuring, b) small tool polishing, and c) MRF.

ULE® CRR Mirror

There are multiple ways in which CRR can be implemented to produce lightweight mirrors for space-based applications. One method uses traditional mirror material and bonding approaches to provide near-term, significant cost and schedule benefits, while minimizing implementation risks. Figure 4 shows how CRR can be implemented when using Corning's ULE® material with low-temperature fusion (LTF) bonding[4], both material and processes that have high technology readiness levels.

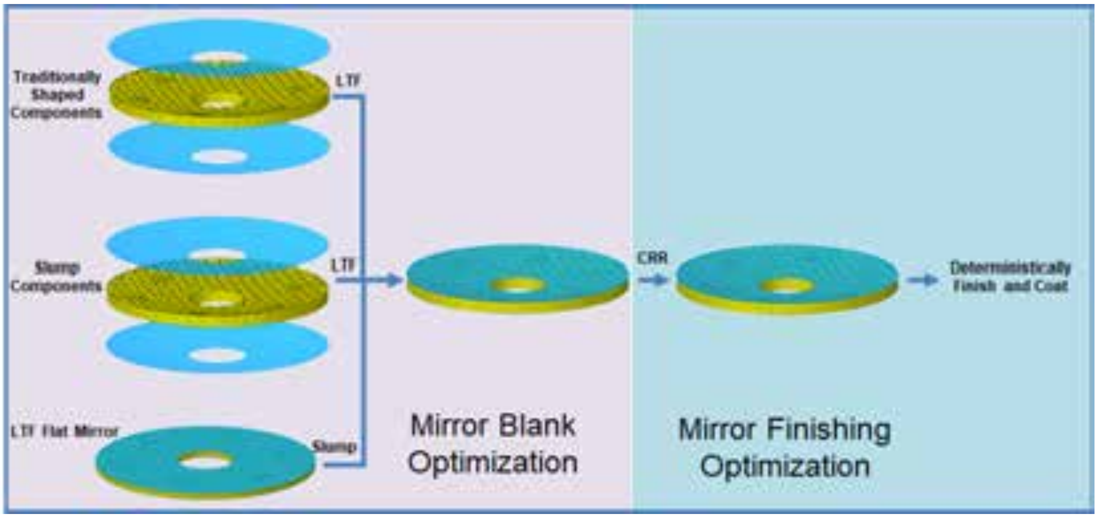


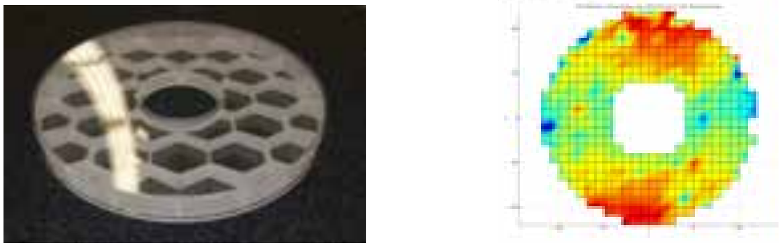
Figure 4: CRR process flow for ULE® mirrors leveraging multiple blank production processes

The optimized implementation of CRR when using traditional ULE® is when the components are fabricated flat followed by LTF bonding and full mirror replication.

Initial development was performed to establish process parameters to enable CRR with ULE® faceplates. These parameters included mandrel material selection, release coating and surface condition definition, process temperature and duration optimization, and pressure application development. The initial trials were performed on small samples and are shown in Figure 5.

Figure 5: CRR development test samples

After identifying appropriate materials and process parameters, tests were performed to slump thin ULE plates at 200 mm in diameter onto a mandrel with a spherical prescription for metrology simplicity. The result of the initial CRR process on a ULE® plate achieved a ~3µm P-V surface figure as measured with a coordinate measuring machine (CMM) with only ~1µm P-V deviation from the actual shape of the mandrel. Additional CRR tests were performed by replicating a ULE® faceplate having a center hole. The faceplate was then bonded to a light weighted ULE® core with a ULE® backplate using LTF. The fully assembled ULE® CRR mirror is shown in Figure 6 along with the resulting surface figure.



(a) (b)

Figure 6: a) CRR ULE mirror and b) surface figure of a CRR ULE mirror as measured with a CMM

The fully assembled ULE® CRR mirror was measured to be ~6.5µm P-V surface figure with ~3µm deviation from the mandrel used for CRR. This result is within capture range of final finishing and meets the requirements for the CRR process.

The process was then scaled to perform CRR on 500 mm class, lightweight mirrors. The results from these tests are shown in Figure 7.

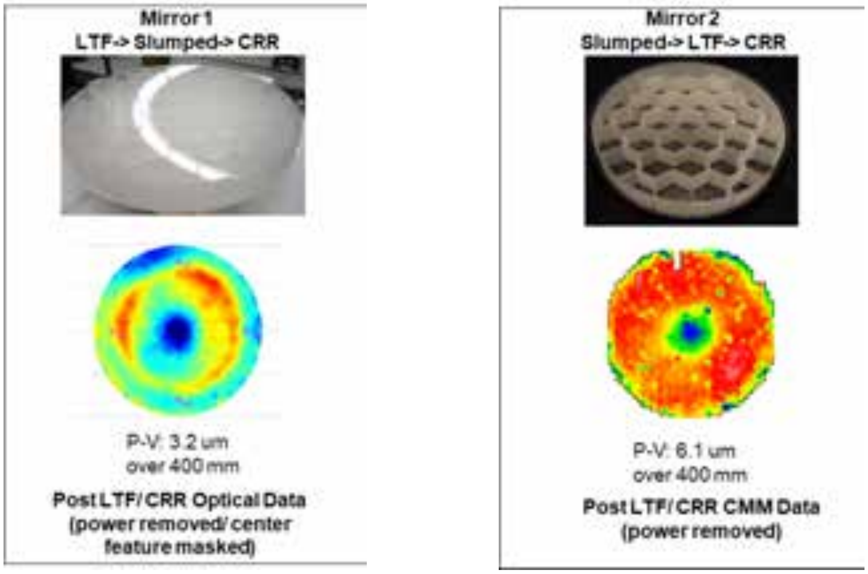


Figure 7: Results of ULE CRR mirror demonstrations

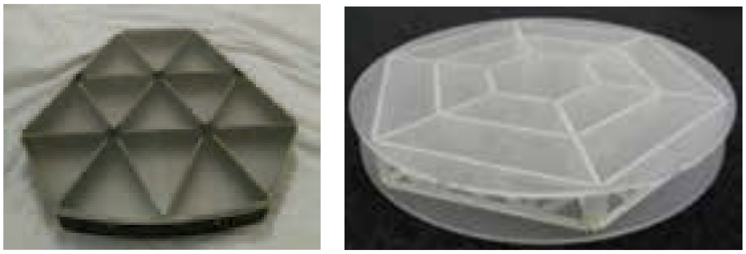
Again, the resulting mirror figure from these tests show that the mirror shape was within capture range of final deterministic finishing to achieve optical specifications.

Constructed Core Mirror

For larger-aperture mirrors, much of the cost and schedule is in the fabrication of the mirror blank. Therefore, in addition to the insertion of replication technologies to optimize mirror finishing, optimization of the fabrication or construction of the mirror blank is required. Harris is investigating blank construction approaches that leverage advanced materials and bonding technologies to reduce the cost, schedule, and mass of the large, lightweight mirror blanks. This technology is called constructed core and a high-level process flow is captured in Figure 8.

Figure 8: Constructed core process flow

The concept of constructed core is to "build" the core as opposed to using traditional subtractive manufacturing processes, such as machining or cutting. The core components can be commoditized by constructing the core using pre-finished composite or ULE® plate material cut to final shape. The core members are then bonded together to create either a large monolithic mirror core or the core segments. The constructed core concept uses pre-finished, flat ULE® plates that are replicated to within capture range of final finishing (CRR) as the front and back mirror surfaces. The plates are then bonded to the constructed core, creating a mirror that is ready for final finishing. Examples of the constructed core technology are shown in Figure 9.



(a) (b)

Figure 9: Examples of constructed core mirror technology: a) composite core and b) ULE® core

3D Printed Architecture for Lightweight Mirrors

Harris is investigating the use of additive manufacturing, or 3D printing, to optimize mirror production, combining the key attributes of the AMC strategy with additive manufacturing of low CTE materials. As in the constructed core concept, the 3D printed mirror concepts will use replicated front and back facesheets made from pre-finished ULE® plates. However, the core structures are printed rather than using traditional subtractive manufacturing methods or construction. This significantly reduces the cost and schedule time line for mirror production, while also enabling new mirror structural designs that reduce the total mirror mass. By using additive manufacturing to print only the structural components of the mirror and not the optical surfaces, the technical challenges associated with additive manufacturing development are significantly reduced. The concept is shown in Figure 10.

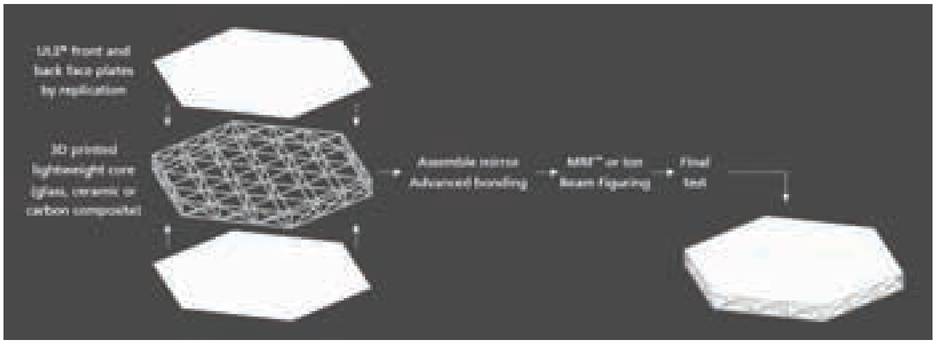


Figure 10: Process flow for 3D Printed Architecture for Lightweight Mirrors

Examples of low CTE mirror cores made with additive manufacturing are shown in Figure 11.

Figure 11: Examples of mirror cores made with additive manufacturing processes

CONCLUSION

Harris has a long history of successfully providing large, lightweight optical components to support space-based imaging missions. We apply an AMC strategy to break the current cost and schedule constraints for large precision mirrors while continuing to pursue future leapfrog technologies. Multiple mirror solutions are being pursued under the AMC strategy to ensure that key near-term and future mission needs are met. Harris has demonstrated the feasibility and scalability of implementing replication to produce stable, ULE® optical components. The initial stages of the AMC strategy are demonstrating the key capabilities needed for future technologies, such as composite mirrors, constructed core mirrors, and 3D printed mirrors to enable future, advanced space-based imaging systems.

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