The Laboratoire d'Astrophysique de Marseille (CNRS-LAM, France)

Building the next generation of optical mirrors

Introduction

Astronomical telescopes and instruments enable astronomers to see into deep space and unravel the mysteries of the universe. Freeform mirror surfaces – surfaces with a shape more complex than a symmetrical conventional mirror surface (as for example, sphere, parabola, hyperbola, etc.) - offer substantial benefits by providing additional degrees of freedom that make it possible to improve the optical performances of the instrument, reducing the overall instrument mass and size.

Freeform optical mirror surfaces must be constructed with nano-scale accuracy to produce clear images. For example, an error of only 2.2 microns on the surface of the primary mirror of the Hubble Space Telescope required one of the most complex space missions in history to correct.

Currently, freeform mirrors are usually produced by computer control optical surfacing and single-point diamond turning, which is expensive and requires long leadtimes. Researchers at the Laboratoire d'Astrophysique de Marseille (one of the public institute in astrophysics of the French National Center for Scientific Research, CNRS-LAM) are developing an innovative manufacturing process based on the plastic deformation of materials and the hydroforming process. Such a technique has the potential to reach these kind of extreme optical shapes and to substantially reduce the time and cost required for manufacturing to demanding tolerance levels. The hydroforming technique deforms the material to its final form thanks to the contact with a specific mold shape in a single step, by applying a fluid at high pressure directly on the optical surface. This method also has the potential to produce a higher quality surface because it eliminates the need for a mechanical tool to contact the mirror surface.

Challenge

The hydroforming process is difficult to design and optimize because the mirror undergoes plastic deformation to provide a freeform optical surface. While the elastic behavior of materials is well known and frequently modeled in optical manufacturing, the analysis of materials under stress in the plastic domain is much more difficult because it involves both material and geometric nonlinearities. One particular importance is the quantifying of the springback effect, in order to control the final shape of the mirror.

In a typical case, the objective is to produce an optical diameter from 100 mm to 300 mm with residual form errors of few micrometers and roughness less than few nanometers rms. Achieving these goals requires analyzing the global structural behavior of the substrate while taking into account work-hardening, anisotropy, contact conditions, boundary conditions and load cases applied during the hydroforming process.

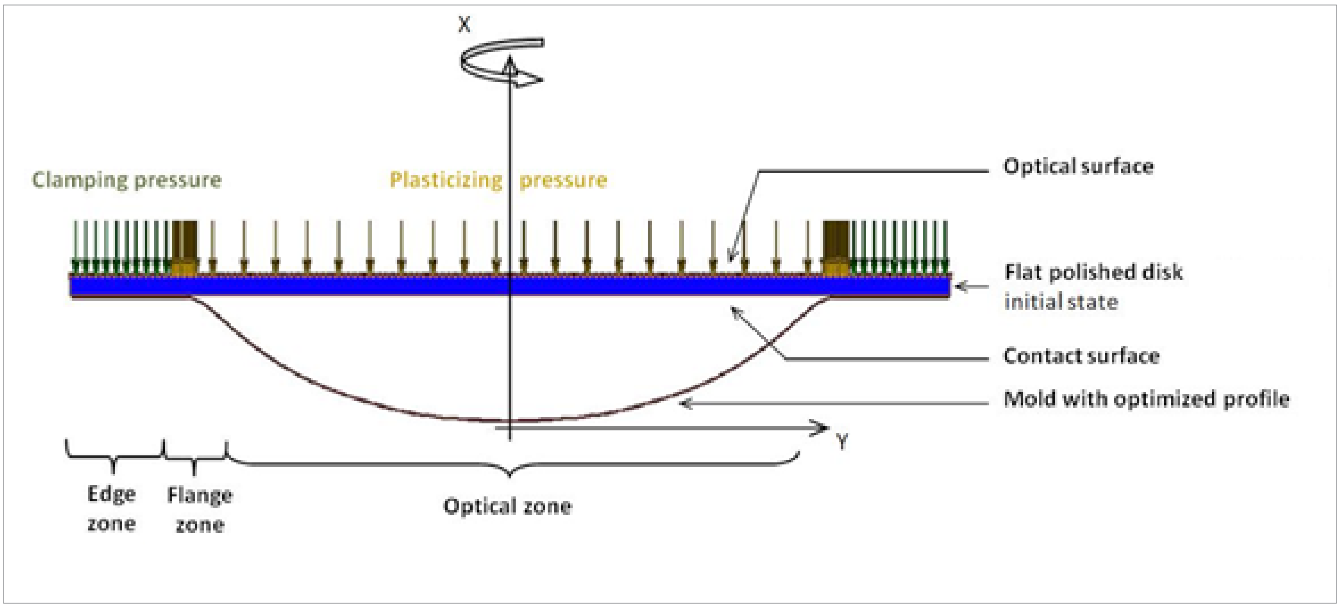

Figure 1: Overview of the principle (©CNRS-LAM)

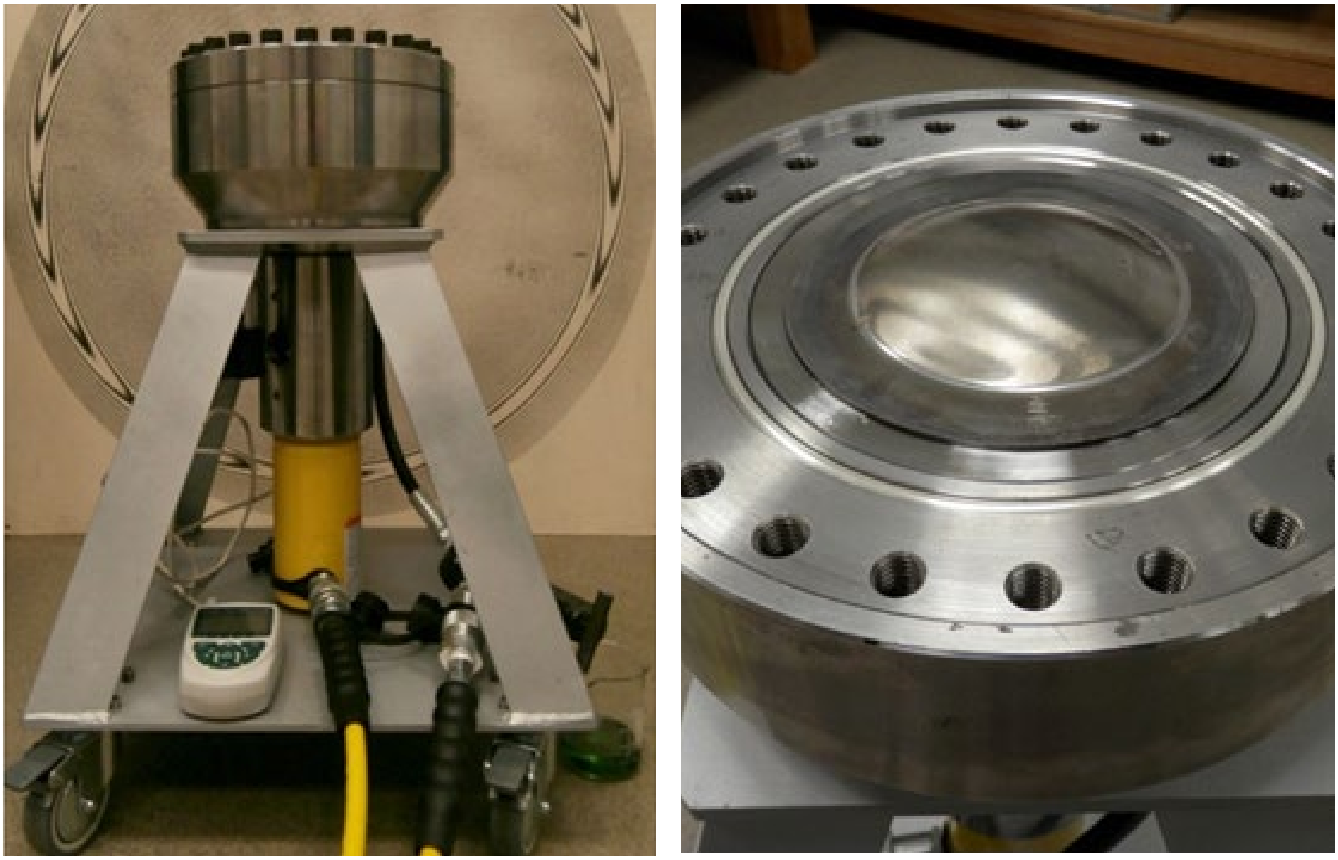

Figure 2: Experimental hydroforming system (©CNRS-LAM)

Solution/validation

“We selected Marc to analyze the hydroforming process because Marc has demonstrated the ability to provide accurate results in problems involving complex nonlinear changes in geometry and materials properties,” said Zalpha Challita, in post-doctoral position at CNRS-LAM. An overview of the hydroforming process is shown in Figure 1. As shown the substrate is divided into three zones. The edge zone maintains the mirror in position and centered within the mold during the hydroforming process. The flange zone is in line with the mold flange to partition the stresses inside the substrate and improve the conservation of plastic deformation after the process. The optical zone is deformed to the freeform shape required by the optical design. A homogenous pressure is applied on the substrate optical zone while a clamping pressure is applied on the edge zone. Materials used include stainless steel, aluminum, and titanium because they possess a large plastic domain, good elastic behavior and the ability to be optically polished.

FEA was performed with Marc to quantify the residual errors after the hydroforming process and to optimize the system. The first step consisted in a coarse model of the system and then refined on the more sensitive parameters which were deduced from real hydroforming tests. The optimized parameters are, for example, hydroforming parameters such as clamping and forming pressures and optical parameters concerning the overall geometry of the initial mirror and of the mold shape. Contact analysis between the mold and the back of the mirror is also performed. The final shape of the deformed substrate after the conclusion of the hydroforming process is then extracted from Marc and treated optically.

Marc can take into account different sets of macroscopic and microscopic material parameters and effects as for example the evolution of the strain and the Young Modulus during the work-hardening and the micro-structural composition of the material. FEA is used to study the springback effect, the accuracy of which depends on the material data and the meshing fineness, according to acceptable time calculation. The main zones of roughness evolution on the mirror surface can also be studied. With Marc so we can manage the analytical aspect of plastic behavior providing very accurate and reliable solving in acceptable time calculation.

The capabilities of Marc in fine tuning optimization allow to match the experimental results according to the error budget of few micrometers authorized in astronomical optics.

Two study cases are presented on figure 4 and figure 5. Because of the fineness of meshing required, according to the micro and nano-scale accuracy, it is preferable to perform 2D and axisymmetrical calculation or eventually a 3D portion. For both cases, the material chosen is Stainless Steel AISI420 for substrates with a total diameter of 140 mm and an optical zone diameter of 100 mm.

In the first case, the mirror has got a thickness of 1 mm only. The desired final shape is a sphere with a focal ratio of F/10, after deformation on a spherical mold aperture of F/2. The mirror was formed with a forming pressure of 15 MPa and a clamping pressure of 10 MPa. The final aspherical optical surface was evaluated after plasticizing following the substrate structural behavior and the springback effect.

The mirror of the second case presents a 2 mm thickness and a focal ratio of F/0.5, after deformation on a spherical mold with the same aperture. The global optical shape obtained here is real extreme and non common on this kind of substrate. This mirror was produced with a forming pressure of 45 MPa and a clamping pressure of 10 MPa.

The second case was much more challenging from a simulation standpoint because it involved application of more than 400 bars of fluid pressure which generated extreme deformation of the substrate. The simulation was also very beneficial in terms of defining the limits of the process and the sensitivity of the final geometry to the various hydroforming parameters.

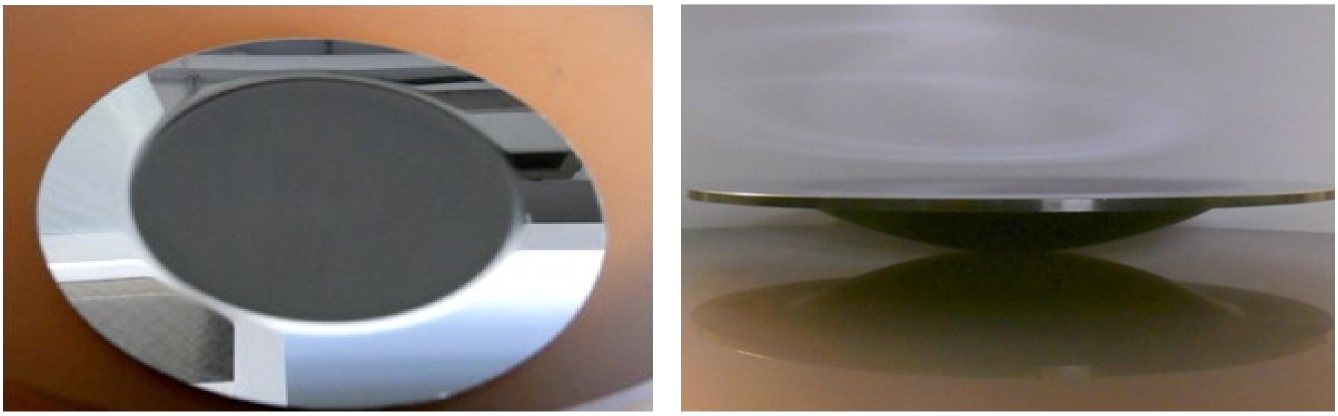

Figure 3: First tests of plastic deformation on optical mirrors (©CNRS-LAM)

Results

“These experiments are innovative because for the first time plastic deformation and hydroforming has been used to produce optical mirrors dedicated to astronomy instrumentation,” Zalpha Challita said. “The highly complex material and geometrical nonlinearities involved in plastic deformation of materials make it essential that accurate and iterative modeling of the process be performed in advance to determine the required mold shape to achieve the desired optical form. Marc demonstrated the ability to accurately model the hydroforming process and will be used extensively going forward.”

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Key highlights:
Product: Marc
Industry: Research institute, astronomical instrumentation
Benefits:
Reduction of time and cost of physical testing
Ability to produce a higher quality mirror surface
Accurate modeling of material and geometric nonlinearities

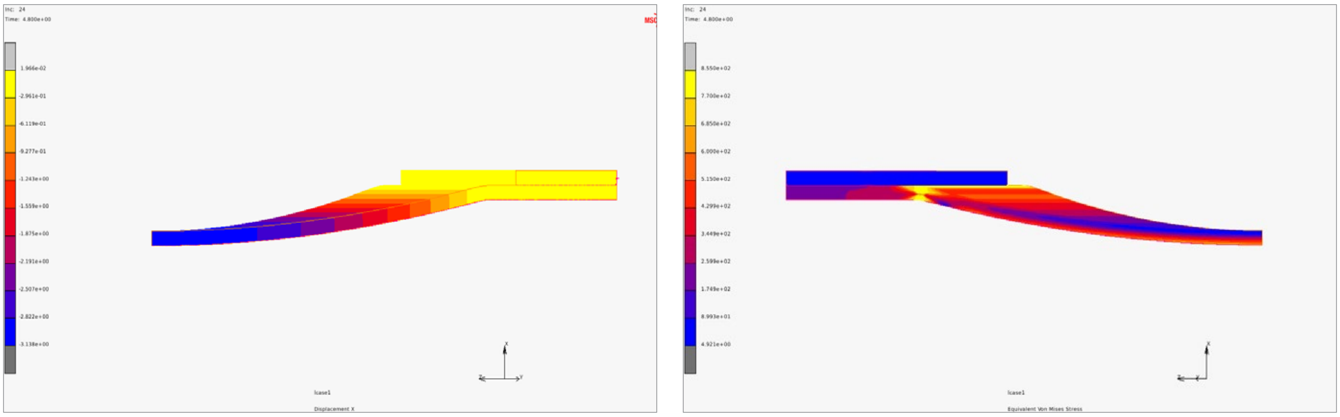

Figure 4: Final shape of mirror as contrasted with mold shape for first study case (©CNRS-LAM

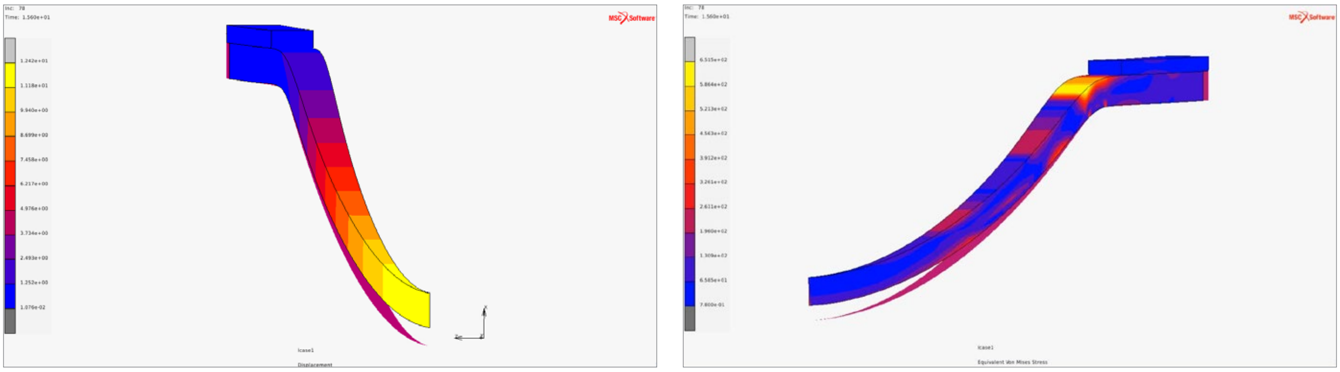

Figure 5: Final shape of mirror as contrasted with mold shape for second study case (©CNRS-LAM)

About the CNRS-LAM

The LAM (Laboratoire d'Astrophysique de Marseille) is one of the most important public research institutes in Europe in the area of astrophysics. It associates fundamental research in astrophysics with technological research in instrumentation. It is one of the few laboratories in France to be qualified to develop instrumentation for space missions. It is a joint research unit (UMR7326) of the French National Center for Scientific Research (CNRS) and the Aix-Marseille University (AMU) with about 50 researchers, 75 engineers, technicians and administrative staff, 15 post-doctoral researchers, 18 doctoral students and 20 contract employees.

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