COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

MICROFABRICATION OF HIGH-ASPECT-RATIO MICROSTRUCTURES BY LIGA TECHNOLOGY (LITHOGRAPHY, ELETROFORMING AND MOLDING)

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Abstract. *The LIGA technology allows the batch production of high-aspect-ratio microstructures from metals, polymers and ceramics. Metallic microstructures like gears, turbines, filters, springs and molds for injection molding or for hot embossing are electroplated in the primary polymer molds produced by lithography. The more usually electroplated metals are Ni, Cu, Cr, Au and Ni-Fe alloys. The metallic molds are used to produce polymer microstructures like gears, turbines, filters, chemical reactors, pumps, lens, prisms, optical waveguides, etc. The typical lateral dimensions of the microstructures are between few microns and few millimeters. Its typical thickness is bellow 500µm*

An almost complete LIGA technology was developed at LNLS, both using the high-precision deep X-ray lithography or the simpler deep UV lithography for primary mold production. This technology is being used for producing polymeric micro-miniature chemical reactors, filters, gears, springs, turbines and flow machines. The typical diameter of the gears are between 470µm and 4000µm, and their typical thickness is between 35µm and 500µm. The same kind of microstructures were also produced from metals, by electroforming Ni, Cu and Au in polymer molds. Metallic molds for production of polymer parts by hot embossing were also produced.
Keywords: *Microfabrication, High precision engineering, Microelectromechanical systems, Mems.*

1. INTRODUCTION

The LIGA technology (Barcher, 1995) (Frazier, 1995) (Ugarte, 1993) (Ehrfeld, 1991) allows the batch production of high-aspect-ratio microstructures (eight/width up to 150/1) from metals, polymers and ceramics. It was born at the Forschungszentrum Karlsruhe GmbH, Karlsruhe, Germany, for producing uranium isotopes separation channels for the Brazilian-Germany Nuclear Agreement on the eighties (Ehrfeld, 1991). It is based on the production of primary polymer molds with sub-micron precision by deep x-ray lithography. The polymer molds are the starting point for mass production of high-aspect-ratio microstructures from metals, polymers and ceramics.

Metalic parts like gears, turbines, filters, springs and molds for plastic injection (secondary molds) are made by electroplating in the primary molds produced by lithography. The more common metals are Ni, Cu, Cr, Au and Ni-Fe alloys. The secondary molds are used for mass production of polymer parts by injection molding or by hot embossing. The mass produced plastic microstructures can be used as tertiary molds for mass production of metallic or ceramic parts. The typical lateral dimensions of the microstructures are in the microns to millimeter range. The typical thickness is bellow 500μm. The precision of the lithographic process may be better than one micron.

PMMA (poly-methil-methacrilate) is the most used resist for deep x-ray lithography. It presents good contrast and good surface finishing (less than 30nm roughness), but needs high radiation dose to be sensitized (bottom dose higher than $2kJ/cm^3$). Then it requires very long exposure times on x-ray sources like LNLS (32m diameter electron storage ring operating at 100mA, 1.37GeV energy).

On ends of 1996 the SU-8 (Despont, 1997) photoresist was announced. It is an epoxy-based negative tone photoresist with chemical amplification, targeted to deep UV (Ultra-Violet) lithography. Thanks to its exceptional transparency to UV, it allow the UV lithography of more than 1mm thick films using the same lithography equipment used on the microelectronics industry. It is a promising material for replacing the PMMA on deep x-ray lithography.

The synchrotron light sources are the most used x-ray sources for deep x-ray lithography (Ehrfeld, 1991), (Vladimirsky, 1995), (Dahlbacka, 1992), (Mohr, 1988), (Ugarte, 1993).

1.1 The deep x-ray lithography process

The basic process of the LIGA technology is the deep x-ray lithography using synchrotron radiation (Ehrfeld, 1991). Its spatial resolution, high accuracy, and possibility of producing high-aspect-ratio microstructures (eight/width < 150) make it an essential tool.

The better wavelengths both concerning accuracy and dose homogeneity are between 2 and 3 Å. PMMA (poly-methil-methacrilate) is the most used resist, and demands a minimal bottom doses higher than 1.6 kJ/cm^3 for complete material removing at the development step. Its maximum dose must be between 20 and 25 kJ/cm^3, and the tolerable dose at the shadow areas of the lithographic mask is 120 J/cm^3. The ratio γ between the top and the bottom dose must be bellow 5 for good development.

Typically, masks (Vladimirsky, 1995) for deep x-ray lithography are made from a 10 to 15μm thick gold radiation absorber patterned on top of a 2 to 3μm thick silicon membrane transparent to x-rays. If the typical wavelength of the x-ray source is 2Å, the lateral Fresnel diffraction caused by the borders of the absorbers is less than 0,2μm for a 400μm thick resist film. The sidewalls are literally vertical, and the aspect ratio may be as good as 150:1.

Alternative masks, less expensive but with smaller mechanical stability, may be made on top of Kapton membranes.

1.2 The deep ultra-violet (UV) lithography process

The lower costs and higher availability of light sources for UV lithography, used on microelectronics, caused the development of the deep UV lithography process (Despont, 1997), that presents the penalty of smaller accuracy and precision. The lateral Fresnel diffraction effects on the borders of the absorbers is higher than on the deep x-ray lithography, because the wavelengths used on UV lithography are in the 280 to 430nm range, and 2 to 6Å on x-ray lithography. It results on 87^o inclined sidewalls, on the best case, and the higher achievable aspect ratio is 17:1.

Typically, masks for UV microlithography are made from chromium absorbers on top of glass or quartz plates. The absorber patterns may be made by electron beam lithography, with 30nm resolution, or pattern generator, when the final resolution is in the 4 µm range.

1.3 Electroforming

Once the primary polymer molds are made over a conductive base, the next step is producing the secondary molds for large-scale production of microdevices, or producing prototype samples of metallic microdevices. Generally, the top surface of the metallic film is rough, so the electroformed film is made thicker than the polymeric form and a lapping operation is applied for smoothing and to trim the thickness. A typical thickness is 200µm ±5µm. The polymeric film is removed, and an optional step of releasing the metallic parts from the substrate can be performed by selectively removing the plating base film.

1.4 Molding

The mass production of polymer, metal or ceramic microstructures is cheaper if plastic molding is used. If it is the case for production of polymer parts, the final product is obtained by injection molding or by hot embossing. If it is the case for producing metallic parts, the primary molds are replicated by injection molding or by hot embossing, and the electroforming of the final parts is made as described above. If it is the case for producing ceramic parts, the primary molds are replicated by injection molding or by hot embossing, and the plastic molds are used for the lost mold production of the ceramic parts.

1.5 Microassembly

Sometimes the LIGA-made parts are assembled on more complex systems. The assembly operation can be made with tweezers and loupe, in the simplest case, or it can be made only by robots or by self-assembly, a technology where spatial rearrangement of the microstructures is induced during the fabrication process.

All the processes described above are for only one level of lithography, but it is possible to make much more complex devices if more than one lithography level is used. Domaining LIGA technology is a priority to LNLS, as expressed on the following objectives.

2 OBJECTIVES

To domain the LIGA technology, the following objectives must be reached:

1) Development of primary molds production technology by deep UV lithography and by deep x-ray lithography using the SU-8 photoresist.
2) Development of the technology for producing Kapton masks for deep x-ray lithography.
3) Investigation of the sensitivity of the SU-8 photoresist to x-rays.
4) Development of the Ni electroforming process in primary molds made by lithography.
5) Electroforming Ni microstructures in SU-8 molds.

3 MATERIALS AND METHODES

Two lithography processes were developed at LNLS for microstructure production: a process based on deep-UV lithography on SU-8 photoresist (SU8-100 from MicroChem Inc.), and other one based on deep x-ray lithography on SU-8. Both processes have all but the exposure step in common.

3.1 UV lithography

A first UV process, for 20μm thick SU-8 photoresist, was developed for producing Kapton masks for deep x-ray lithography. The resist was spinned at 3000rpm for 20s, then baked on owen at 95^{o}C for 40min, then contact exposed to UV at 200mJ/cm^{2}, then baked at owen at 95^{o}C for 60min, then developed for 70s under stirring. Similar procedure was established for thicker films, changing only the exposure and baking times.

3.2 X-ray lithography

It differs from the UV process only at the exposure step, that is made under white synchrotron beam (λ_c~6Å), using the appropriate Kapton masks made by the above descrived UV technology.

A 125μm thick process was developed for producing general-purpose microstructures. The same patterns were lithographed both by UV and by x-rays, for comparing both processes. SU-8 films were produced by spinning at 1000rmp for 30s, with 5s accelerating ramp, on <100> Si substrate and on stainless steel substrate. The baking procedures were as described above.

3.3 Kapton Mask

The Kapton masks were made by electroless deposition of 1.8μm thick Au absorber film on top of a 25μm thick Kapton membrane. The plating seed layer was an Au/Cr (2000 Å and 200Å, respectively) evaporated film. The resist form for delineation of the radiation absorber pattern was made by the 20μm thick deep UV lithography process described above.

3.4 The x-ray exposure station

The Instrumentation Beamline of LNLS was used in this experiments. Its beam divergence is 10mrad horizontal and 0.3mrad vertical, and its overall size is 100mm width by 3mm height at the exposure chamber, 10 m away from the radiation source.

The exposures were performed under $2x10^{-2}$mbarr vacuum. The radiation beam was filtered by a 125µm thick Be film, a 300µm thick Kapton film, and a 37.5µm thick Al film before reaching the Au absorbers of the lithography mask. The radiation beam received an additional filtering by a 2µm thick Au absorber film, at the dark regions of the mask, and of a 20µm thick SU-8 film at the light regions of the mask. The samples were exposed for different exposure time, when they were moved in front of the radiation beam at 1cm/s speed on a 5cm long path.

The resulting microstructures, on both cases, were inspected and measured on electronic scanning microscope.

3.5 The electroforming process

Once verified the satisfactory quality of the deep lithography processes, several samples of SU-8 100 on stainless steel substrate (1½" diam., 1mm thick) were lithographed on UV and submitted to pulsed Ni-Cl platting at ambient temperature, such that the adequate current density was reached.

4 RESULTS

The 20µm thick UV lithography process developed for x-ray masks production shows be capable of producing microstructures free from cracks and peeling, that means a small level of residual stress, and shows good reproduction of the patterns from the lithography mask (**Fig. 1**).

Good results were also obtained on top of Kapton membranes, for production of the Au absorber patterns on x-ray masks, as described above. The SU-8 forms had no problem under the 8 hours long electroless Au plating bath at 90°C, that produced 1.8µm thick film, as measured on a profilometer (**Fig. 2**).

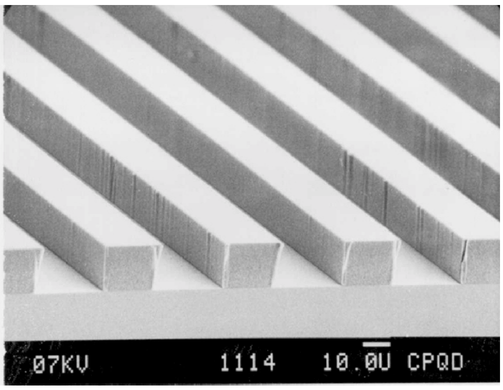

Figure 1: 20µm thick, 20µm wide lines, made by deep UV lithography on SU-8 25 photoresist.

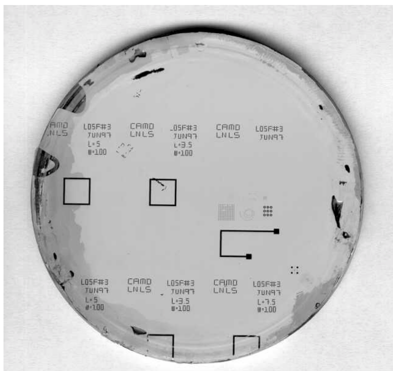

Figure 2: Kapton Mask for deep x-ray lithography. The dark areas are transparent to x-rays. The radiation absorber is a 2µm thick Au film (1.8µm from plating and 0.2µm from evaporation).

The best results from the Kapton masks test on deep x-ray lithography were obtained for 60s exposure time on 125μm thick SU-8 100 film. Its performance is shown on **Figures 3 and 4**, where it is compared to the deep UV lithography performance.

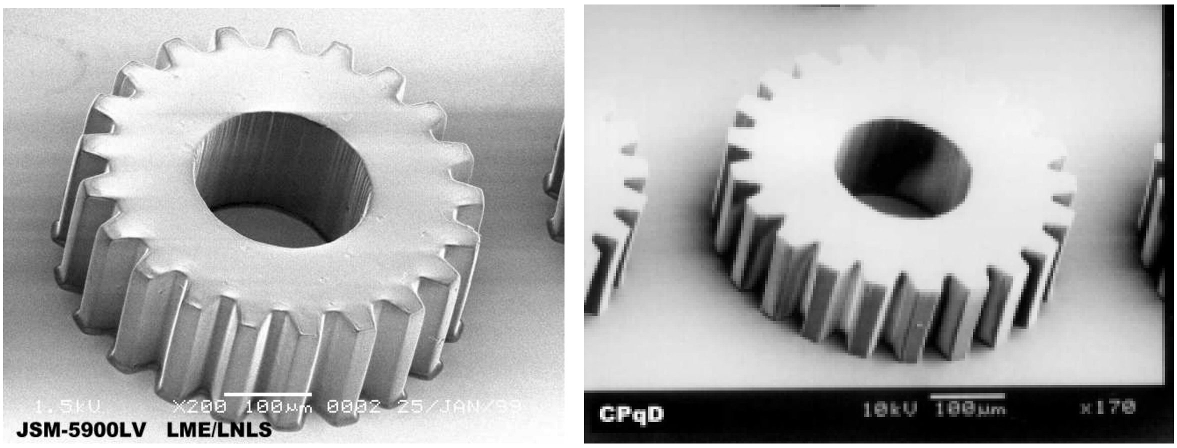

Figure 3: 125μm thick, 470μm diameter, SU-8 gears. The left gear was produced by deep x-ray lithography. The right gear was produced by deep UV lithography. The verticality of the sidewalls and the fidelity of the tooth shapes is clearly superior on the left gear.

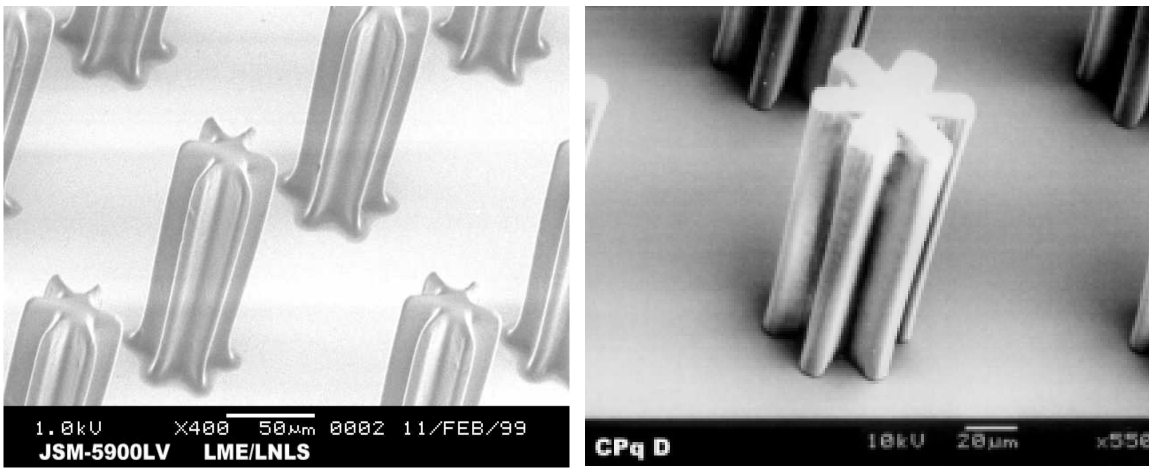

Figure 4: Primary molds (125μm thick) for production of spinnerets for textile industry. The left sample was produced by deep x-ray lithography, and its sidewalls are vertical and have 10μm width. On the right is the sample produced by deep UV lithography. Its sidewalls are inclined because border diffraction on the lithography mask.

The curves on **Figure 5** show the calculated power spectrum at: 1) the synchrotron source, 2) after a 50μm thick Si absorber, if it was after the Be filter, 3) after the absorbers of the Kapton mask.

Simulation shows that the Kapton mask plus the 300μm thick Kapton film filter and the 37.5μm thick Al film filter could be be replaced by a 50μm thick silicon membrane mask. The Si membrane replaces the actual filters and at the same time replaces the Kapton membrane of the Kapton mask.

The integrated base dose for the 125μm thick SU-8 film, on the light areas of the Kapton mask, for 60s exposure time, was $70 J/cm^3$, much smaller than the minimum dose for PMMA ($2 kJ/cm^3$).

The first microstructure electroforming essay on Ni-Cl bath produced a more than 200μm thick film after 4 hours deposition. Its surface was very rough, and the film peeled from the substrate, causing also the peeling of the surrounding SU-8 film (**Fig. 6a**). The following essay, with smaller current, produced a more uniform, 130μm thick Ni film, and presented peeling only in small areas both of the Ni film and of the SU-8 film (**Fig. 6b**). The best results were a very smooth, 70μm thick Ni film, with no signal of peeling. The optimal current density was $10 mA/cm^2$ (**Fig. 6c**).

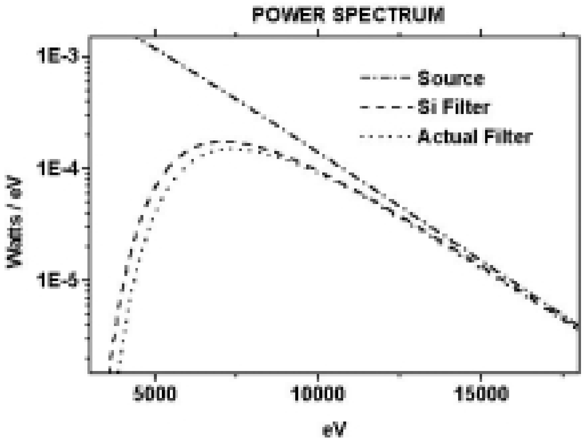

Figure 5: From top to bottom, the curves show the calculated power spectrum at: 1) the synchrotron source, 2) after a 50μm thick Si absorber, if it was after the Be filter, 3) before the Au absorbers of the Kapton mask.

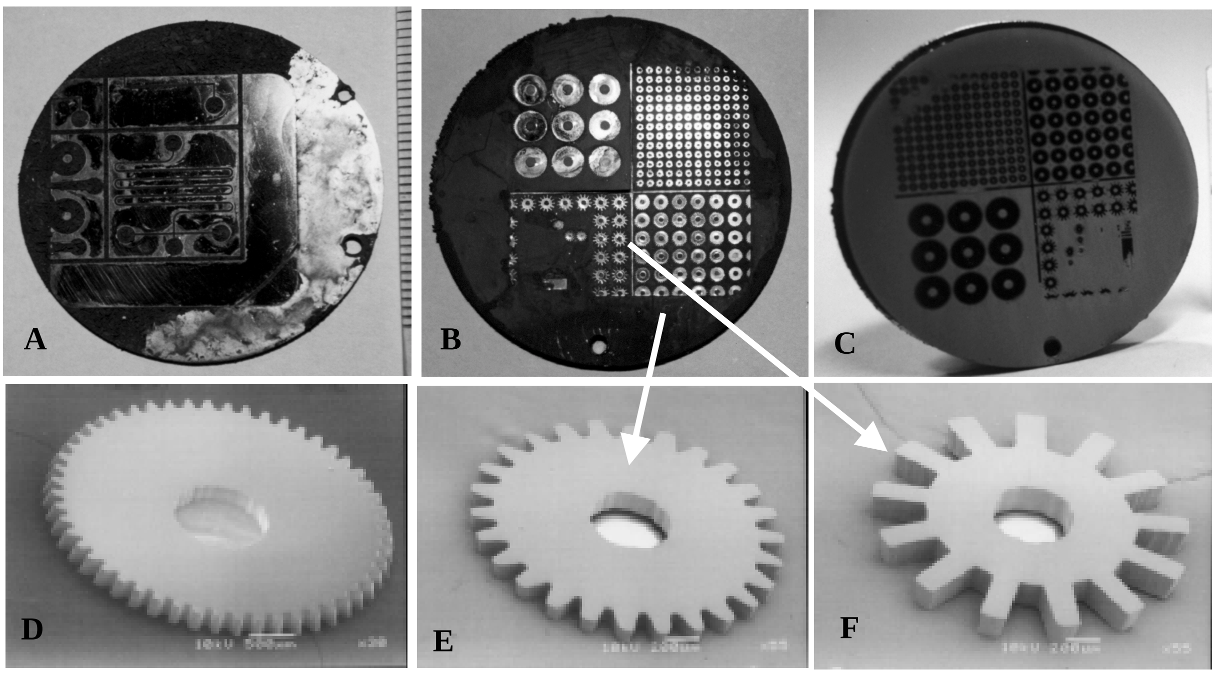

Figure 6: A) First Ni platting essay: form for a chemical reactor. High stress 200μm thick Ni film. The Ni and SU-8 film presented peeling. B) Second Ni platting essay: gears and turbines. Middle stress 130μm thick Ni film. The Ni film (dark areas) and the SU-8 film (light areas) presented peeling. C) Third Ni platting essay: gears and turbines: 70μm thick Ni film (light areas) with no signal of peeling. The figures D, E and F are the gears and turbines from the figures B and C: D) Primary mold for a 4mm diameter, 52 tooth gear, E) Primary mold for a 2mm diameter, 26 tooth gear, F) Primary mold for a 2mm diameter turbine.

5 DISCUSSION

Results show that it is possible to produce, by deep UV and by deep X-ray lithography on SU-8 photoresist, primary molds for producing metallic microstructures, both by electroless deposition and by electroforming. The SU-8 100 photoresist shown good sensitivity to both UV and x-ray radiation. Good results were obtained for SU-8 100 exposure to x-rays in the 5-15keV energy range. Some effects of the substrate fluorescence can be noted (the widening deformation on the base of the microstructures), that can be solved by addition of a low-Z film under the resist film.

Best results for deep UV lithography were obtained for $10mJ/cm^2/\mu m$ dose, and the best results for deep x-ray lithography were obtained for $70J/cm^3$ bottom dose. It is clear that the x-ray process produces much better definition of the microstructures, and nearly vertical side-walls, and that the UV process produces side-walls with, at best, 87^o from the substrate.

Short exposure times on SU-8 exposure to x-rays, if compared to PMMA exposure times, make viable the mass production of microstructures by deep x-ray lithography generated by a synchrotron source like LNLS.

High sensitivity of SU-8 to x-rays in the 5-15 keV energy range makes viable the creation of a new mask technology based on 50µm thick Si membrane substrate, instead of the conventional 2µm thick Si membrane. It can pull down the price of the masks and make it more mechanically stable, and more handling resistant.

Good contrast of the SU-8 photoresist was evidenced by the relation between the bottom dose under x-ray exposure on dark areas ($24J/cm^3$) and on light areas of the mask ($70J/cm^3$). It means that the Au absorber patterns do not need be very thick to achieve sufficient contrast, resulting on cheaper and more easily manufactured masks.

The SU-8 forms used both to electroless plating and to Ni electroforming shown excellent resistance to chemical attack at high temperature, presenting peeling only when the plated film have high stress.

Several batches of Ni gears and turbines with diameter from 1mm to 4mm and thickness around 100µm were made. The micron size details of that's devices were well reproduced.

6 CONCLUSION

The batch production of high-aspect-ratio microstructures by LIGA technology at LNLS was demonstrated. For reaching this result, the technologies of deep UV lithography and deep x-ray lithography on SU-8 photoresist were dominated, a technology for producing Kapton masks for deep x-ray lithography was developed, an electroless Au platting process was developed, and a process for Ni electroforming on SU-8 molds was developed.

Two other important results were obtained. The viability of mass production of microstructures by deep x-ray lithography on SU-8 using the LNLS´ accelerator, and the possibility of development of a new mask technology based on 50µm thick Si membrane substrate, that replaces the conventional 2µm thick Si membrane technology. It can pull down the price of the masks and make them more mechanically stable and more handling resistant.

Acknowledgments

The authors express their gratitude to the support from LNLS and CPqD, and to Prof. Jacobus Swart, from CCS/UNICAMP, that helped us with the electroless gold plating bath used to the Kapton masks production. Part of the electron microscopy work has been performed with the JSM-5900LV microscope of the LME/LNLS.

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