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PMMA Lens Arrays for Micro Concentrator Solar Cells Produced by Hot Embossing

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Abstract

The rising energetical needs of modern society have been increasingly pushing for the improvement in energy efficiency. Thin-film solar cell technology encompasses several types of devices whose purpose is to gather energy emitted from a luminous source and convert it into usable electrical energy for a variety of applications, particularly low-powered devices. Micro concentrator solar cells are promising devices to solve the materials availability problem and address the power conversion efficiency simultaneously. Since the energy conversion efficiency for this type of solar cell is not particularly high, it stands out to benefit greatly from using an optical concentrator element to increase the light intensity reaching the active surface. The micro-concentrator element is comprised of a micro-lens array, which can be manufactured by different technologies, such as polymer injection moulding, extrusion, or hot embossing. In this work, we explore how hot embossing can be used to inexpensively produce spherical lenses with Ø 1 mm in an array according to micro concentrator solar cell requirements. A simple compression system coupled with an infrared lamp heat chamber was used to emboss PMMA disks. Different mould insert manufacturing technologies were used and different hot embossing parameters were assessed. The process replicability of the micro-lens cavities was determined by infinite focus microscopy and optical microscopy. The most promising lens array was achieved with a mould insert produced by µ-EDM (with Ra and Rz values of 0.6 µm and 4.58 µm, respectively).

Author Keywords. Hot Embossing. PMMA. Micro Concentrator Solar Cells. EDM. CNC.

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1. Introduction

Global concerns regarding rising energy needs have fostered research in several different areas towards developing and optimising energy harvesting technologies. Solar cells are an example of an attempt to increase sustainability of gathering irradiated sunlight and converting it into electricity. This technology has known considerable improvements to its energy efficiency in the last decades. However, physical limits to its theoretical energy harvesting capacity remain in place with the materials currently used due to the Shockley Queisser limit for single junction solar cells (Cheng and Barriere 2019). In current operating circumstances, the power conversion efficiency values of affordable solar cells are still considerably below the theoretical maximum value of 33.6 %, though, owing to a variety of solar cell fabrication limitations and their light-gathering ability (Cheng and Barriere 2019; Mann et al. 2016). The use of concentrator elements above the solar cell is a straightforward solution to raise the overall energy efficiency of the solar cell by focusing the sunlight onto the active surface of the solar cell, which in turn leads to increases in the power conversion efficiency of the system (Green et al. 2021).

Hot embossing is a flexible moulding process that allows the production of delicate micro details with high aspect ratios (Colafemina, Militão Dib, and Jasinevicius 2021; Deshmukh and Goswami 2019). This process is relevant to producing polymeric micro-components due to the low cost of the moulds, the excellent reproducibility, and the fact that it is a simple process (Huang et al. 2011; Kuo and Wang 2014). There are several ways to perform hot embossing with polymeric materials; depending on the process and the material under use, the parameters and steps must be adjusted. In general, mould inserts are manufactured by lithography followed by electroforming or fabricated through machining operations such as micro-milling, micro-electrical discharge machining (µ-EDM), laser operation, etc. The major challenge faced during hot embossing is to optimise the process parameters to ensure the replicability of the cavity on the embossing mould insert with the work material to achieve maximum accuracy (Li, Li, and Gong 2014). Polymethyl methacrylate (PMMA) sheet is commonly used in hot embossing as a work substrate for different applications (Green et al. 2021). For optical applications produced by hot embossing, PMMA is an affordable choice with a common refractive index variation between 1.48 to 1.50 for 350-1600 nm wavelengths, 95% light transmittance and a glass transition temperature range (Tg) of 100-110 °C (Yuan et al. 2021; Moore et al. 2016; Pan et al. 2011). Different technologies have been assessed as viable options for the production of mould inserts for hot embossing of polymer lens arrays: micro-milling (Green et al. 2021), conventional vertical CNC milling (Peng et al. 2014; Shamsi et al. 2014) and µ-EDM. In this work, it is proposed to study the influence of the different milling technologies and materials for mould insert production while using identical hot embossing parameters.

2. Materials and Methods

This study encompasses different steps: mould insert manufacture and characterisation, insert application in hot embossing towards producing PMMA microlens arrays and their subsequent characterisation.

2.1. Mould insert manufacture

Three different technologies were used to produce three mould inserts, reproducing the design in Figure 1. The mould insert design is the result of micro concentrator solar cell requirements and layout. However, the total number of mould insert cavities only equates to a small representative area of the overall micro concentrator solar cell device. Each mould insert encompasses 13 cavities, with a 1.0 mm internal diameter and a depth of 0.5 mm, as seen in Figure 1. The design choice sought to have a representative area of a hexagonal disposition of the microlens array. Three different materials were used to produce the mould inserts (Table 1).

Production Technology	Mould Insert Material
CNC Milling	Brass
EDM	DIN HS6-5-3-8
M-EDM	DIN 1.2083

Table 1: Mould Insert Material and Technology

The advantage of μ-EDM over conventional EDM is greater dimensional control due to a decrease in the size of the tooling used and corresponding finer control over the adjustments to process parameterization.

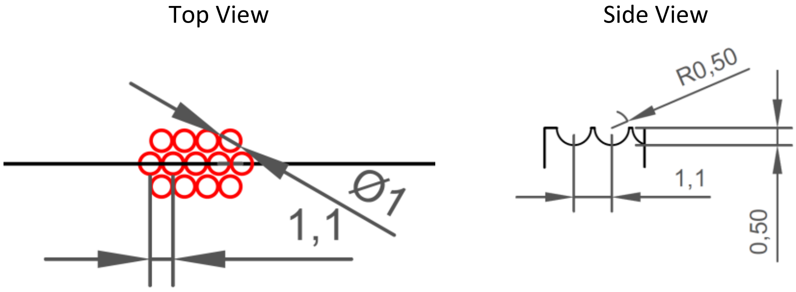


Figure 1: Microlens cavity design at the mould insert

The profile and depth of each of the mould centre cavities were determined by digital optical microscopy (LEICA Microsystems DVM6 Digital Microscope, LEICA, Wetzlar, Germany).

The roughness study of the mould centre cavity of each mould insert was carried out resorting to focus variation microscopy (Alicona InfiniteFoucs G4, Alicona Imaging GmbH, Raaba/Graz, Austria) according to ISO 4287: 1997 and ISO 4288: 1996.

The finishing of the produced lens arrays is considerably influenced by the choice of the production technology employed in the fabrication of the mould inserts. As such, roughness value of each production method explored should induce differences between all arrays. In terms of production cost, CNC milling is the least expensive technology used in this work, whereas μ-EDM is the most expensive by a factor of 5.2 times the obtained cost of the EDM option for an identical configuration.

2.2. Hot embossing: Micro-lens array production

The micro-lens arrays were manufactured by hot embossing laser cut 30.0 mm diameter disks of 1.3 mm cast PMMA sheets (Goodfellow, Coraopolis, PA, USA) using three different mould inserts produced by the processing technologies indicated previously, as represented in the schematic in Figure 2. The arrays were hot embossed at 170 °C for 20 minutes holding time after applying a 10 °C/minute heating rate. The pressure was maintained throughout the complete duration of the holding stage, which started immediately after reaching the set target temperature. The pressure was immediately relieved at the end of the holding stage, and the system was left to cool for 10 minutes before demoulding the lens array. Different embossing pressure values of 5.0 and 10.0 MPa were tested using a Lloyd Instruments LR 30K (Lloyd Instruments Ltd, West Sussex, UK) tensile test machine in compression mode, coupled with a Quad Ellipse Chamber IR lamp-heating heat chamber (Research Inc., Minneapolis, MN, USA) until the PMMA surface accurately reproduced the mould insert geometry.

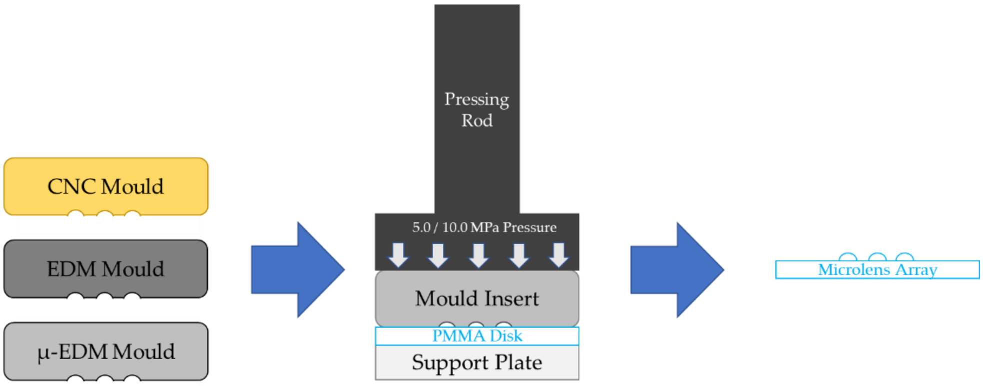


Figure 2: Schematic representation of the hot embossing step

3. Discussion

3.1. Mould insert characterisation

The mould cavities of the metallic inserts were analysed by digital optical microscopy (DM), as shown in Figure 3, to gather topographical data from the mould inserts in addition to the image capture. The threads from the milling tip can be seen on the CNC-milled brass insert, whereas the steel mould inserts show considerably different roughness values as the result of the specification differences inherent to the EDM and μ-EDM processes.

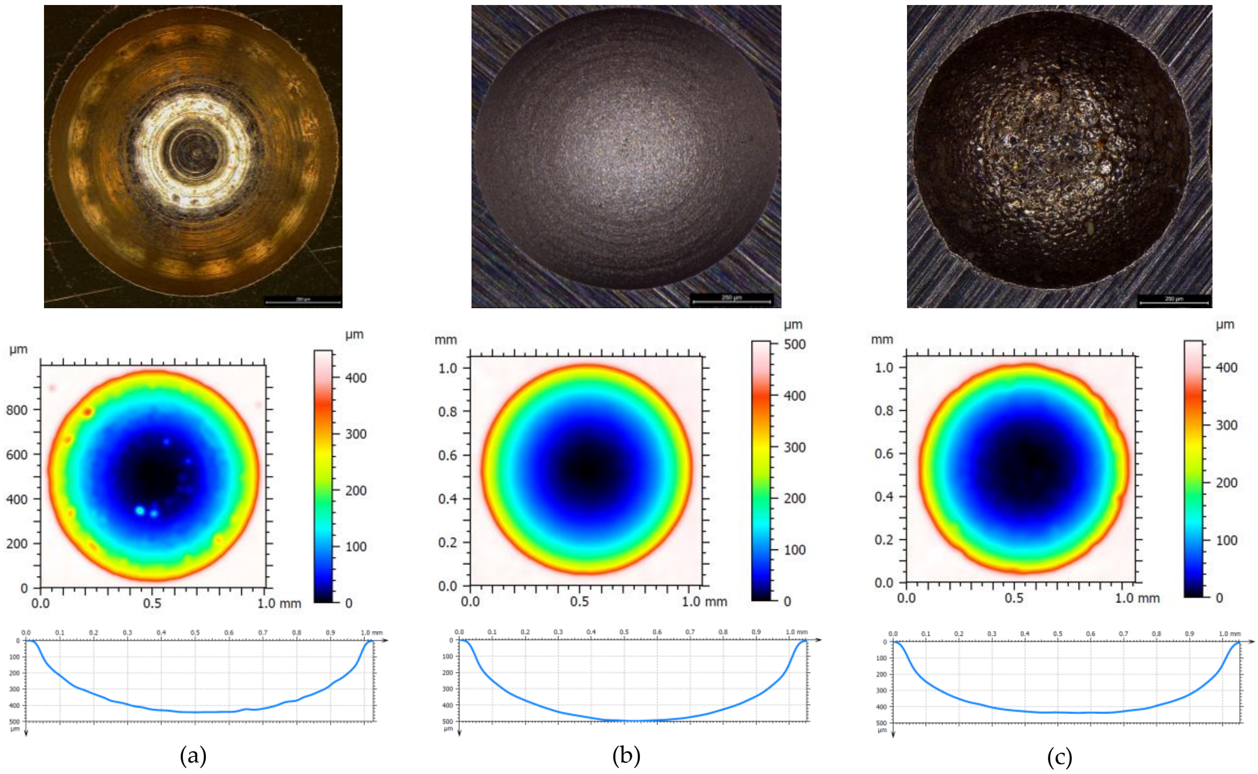


Figure 3: DM image of centre cavity , topographical data and depth profile of the mould inserts manufactured by CNC milling (a), μ-EDM (b) and EDM (c). Scale bars correspond to 250 μm

Analysis of the depth of each of the mould inserts centre revealed shallower cavities for both the CNC-milled part and the EDM-produced insert, as digital optical microscopy measurements indicated cavity depths of 441 and 440 μm, respectively. The cavity depths produced by μ-EDM were closer to the defined value at 510 μm, as seen in Figure 3(b), using the same measurement methodology. All cavities observed revealed a profile that deviated slightly from the intended spherical geometry, exhibiting a cup shape instead, illustrating some of the process limitations of the manufacturing technologies selected.

Roughness measurements obtained by variable focus microscopy according to ISO 4287:1997 and ISO 4288:1996 are visible in Table 1, revealing average roughness values of the milled brass mould insert close to those observed for the µ-EDM produced insert.

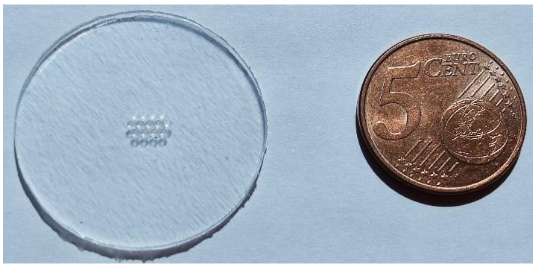
Mould Insert	Ra (µm)	Rq (µm)	Rz (µm)	Profile Length (mm)
Brass (CNC milled)	0.65	0.80	5.17	5.35
DIN 1.2083 (µ-EDM)	0.60	0.78	4.58	5.67
DIN HS6-5-3-8 (EDM)	6.04	7.17	43.79	15.75

Table 2: Roughness values of each of the measured profiles

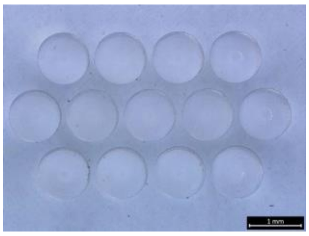
The surface roughness analysis of the mould inserts revealed that average roughness Ra and Rq values of the vertical milled and µ-EDM were very similar, with the most significant difference being the Rz. This result indicates that µ-EDM is seemingly competitive with precision CNC milling regarding the roughness values of the milled surfaces. The EDM-produced mould insert exhibited a considerably rougher surface, as denoted by the substantially higher values for the previously mentioned properties. This result is coherent with the processing conditions used for EDM manufacturing (Ramasawmy and Blunt 2004).

3.2. PMMA lens array

An example of a PMMA lens array after demoulding is shown in Figure 4.



(a)

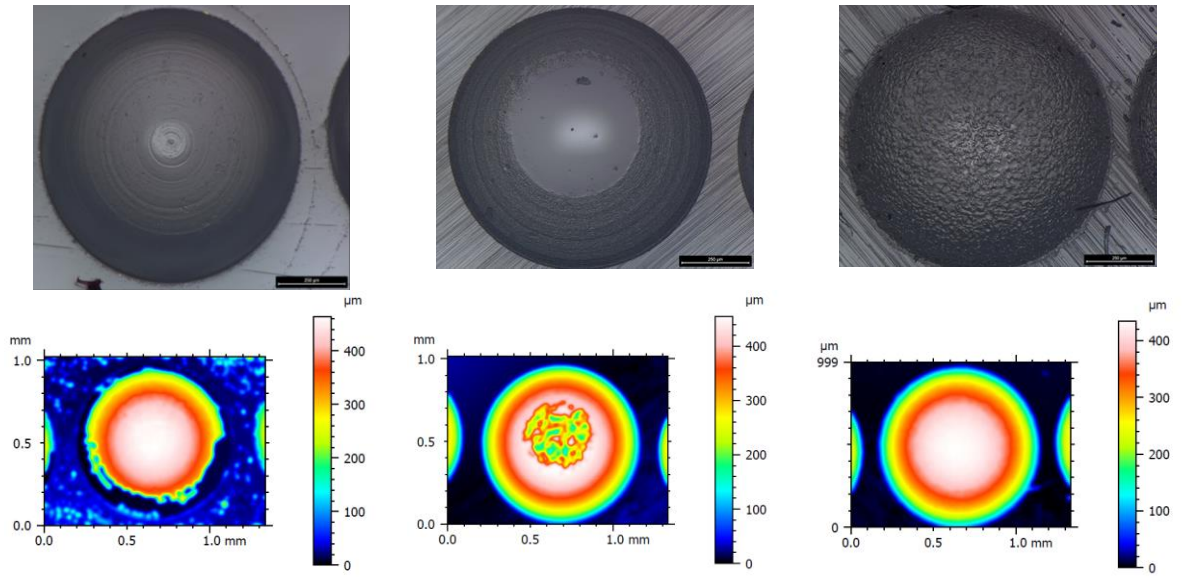


(b)

Figure 4: Microlens array produced using the EDM mould insert (a) and DM image of lens array produced with µ-EDM mould insert (b)Scale bar is 3 mm

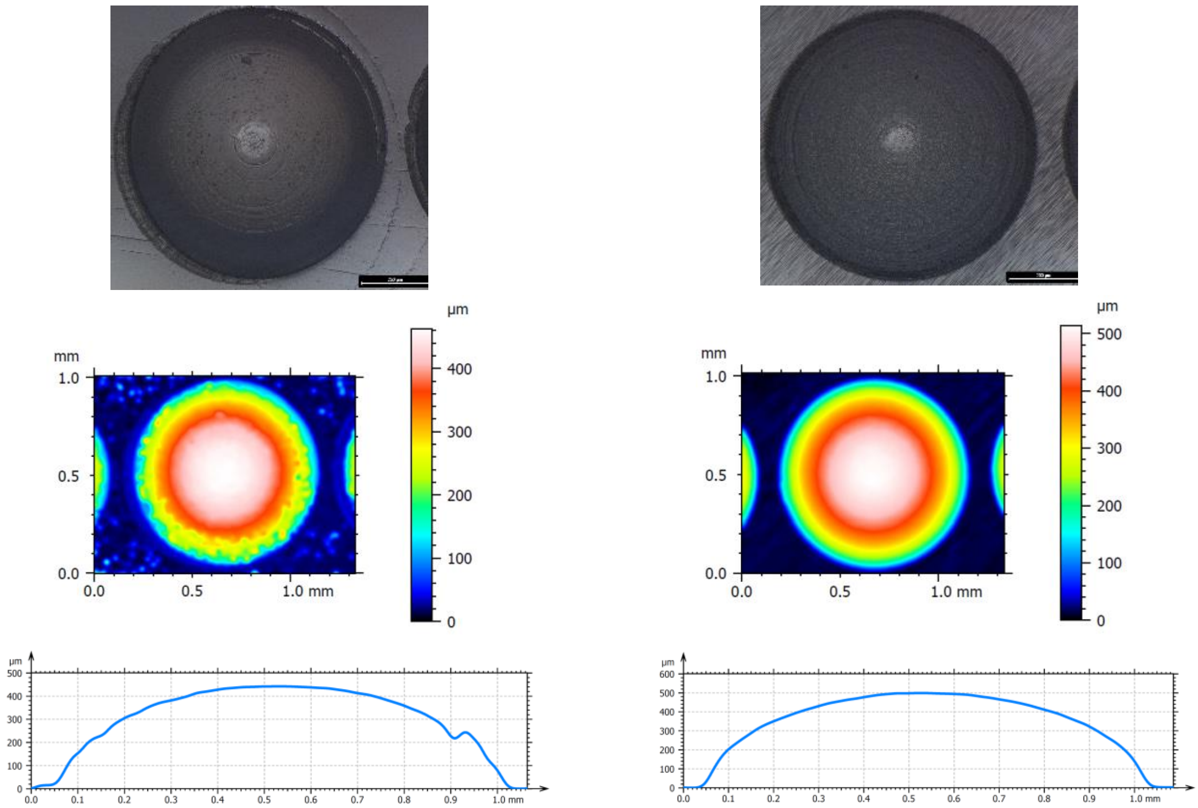
The 5.0 MPa pressure value used for embossing only partially replicated the mould topography for the brass and the µ-EDM mould inserts, as revealed by the maximum height of the topographical maps in Figure 5, which differ from the measured depth of the mould inserts. Analysis of the lens produced using the brass mould insert revealed a depressed outer perimeter of the lens, not corresponding to the intended hemispherical geometry. The insert produced by µ-EDM did not have its centre completely embossed by the mould cavity for this set of processing conditions, as evidenced by its smooth central region which did not replicate the mould cavity details. The smoothness of the central region, however, could prove a benefit to overall power conversion efficiency as a partially-filled approach, as a lack of full replication of the mould surface defects could translate to better concentration factors of the lenses (Moore et al. 2016). Surface roughness of the lens produced by the EDM mould insert indicates that the PMMA completely penetrated and was successfully conformed by its respective cavity for these processing conditions.

The 10.0 MPa pressure value used yielded the results visible in Figure 6. The pressure used was high enough to replicate the geometry and surface features of the mould cavities onto the PMMA disks. However, in the case of the µ-EDM insert, the centre part of the central lens does not fully replicate the insert geometry under the applied pressure value. To fully replicate the insert mould geometry, according to the literature (Li, Li, and Gong 2014), temperature and time should be raised. However, the non-replication of the mould insert could prove advantageous for this application (Moore et al. 2016), as it allows for the creation of a smoother surface that will be more adequate for concentrating sunlight with a smaller energy loss.



(a) (b) (c)

Figure 5: entre micro-lens and topographical data of the brass mould insert (a), of the µ-EDM mould insert (b) and of the EDM insert (c) produced at 5.0 MPa. Scale bars correspond to 250 µm



(a) (b)

Figure 6: DM image, topographical map and profile of the centre micro-lens embossed by the brass mould insert (a) and of µ-EDM mould insert (b) produced at 10.0 MPa

4. Conclusions

Evaluation of the different processing technologies for the creation of the intended hemispherical morphology showcased some of the limitations of each of its respective methodologies. The dimensional control of the cavities produced showed that μ-EDM allowed for production of the most dimensionally accurate cavities out of all the analysed solutions, as deviation from the intended maximum depth was only circa 10 μm. Both vertical CNC milling and conventional EDM were unable to accurately control the depth of the intended cavities to the specified dimensions.

The processing conditions employed were successful in producing PMMA micro-lens arrays, with a 5.0 MPa pressure proving sufficient for fully conforming the PMMA disks using the EDM mould insert, whilst both other mould inserts required a 10.0 MPa pressure to achieve the intended result. The production cost of these lens arrays is estimated to be greatly influenced by the cost of manufacturing the corresponding mould insert, with CNC vertical milling offering the most cost-effective way to produce a low-roughness cavity for lens embossing.

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