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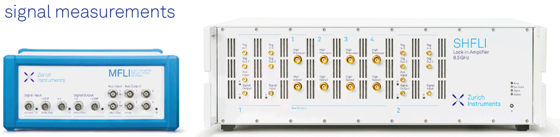

Process Systems Engineering for Sustainable Photographic Lens Production: A Review

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Abstract. Photographic lens is an invention to duplicate human eye functions and operations. Starting with seeing and focusing the object, the lens then transmits lights containing information of the scene such as colours, brightness and shapes to the digital sensor or photographic film. To produce such invention, it comprises complex steps which include material selection and processing, lens machining and finishing. Being the first of its kind, this paper will review the roles of process systems engineering (PSE) in the manufacturing of sustainable photographic lens from R&D and commercial angles. The review will detail PSE contributions for each of the step and highlights the related challenges in implementation.

INTRODUCTION

Photography is a method of capturing object by using light that transmit through a photographic lens and process the captured object onto a film (traditional camera) or a digital sensor (modern camera). Film provides a photochemical reaction to the light, while sensor performs a photoelectric reaction with light [1]. In other words, both film and digital sensors react cumulatively to the light sources as to serve all photographic purposes such as for artistic, scientific or informative. These purposes can be handled using a tool called as camera which has the body in one end, and the lens at another end. The camera body contains components other than lens such as shutter, mirror, sensor, viewfinder, pentaprism, screen, processor and battery. The camera lens houses optical glass, aperture ring, focusing control and focal length control [2].

High quality lenses are in a combination of flawless optical glass that are perfect to focus the scene in front of the camera, bring in the light while mapping the scene and fall onto the digital sensor. Lenses with different sizes provide different purposes based on their focal length, measured in millimetre (mm). The smaller the length, the wider the view the lens will capture. The longer the focal length, the closer and narrower the view. Manufacturing of different lenses require specific steps, relentless precisions and quality assurance procedures, as to ensure fulfilment of those photographic purposes with superior image quality. Typical issues associated with lens production include materials acquisition and selection, machines versus men job scopes and reliabilities, cost and market expectations, and so on. In order to systematically synthesize, design and analyse the lens production processes, Process Systems Engineering (PSE) is identified as the most promising engineering discipline to resolve the abovementioned issues, similarly can be expected for other industries in sustainable manner [3]. Being the first of its kind, this paper focuses the review of the contributions of PSE in photographic lens production processes. It will first describe the lens manufacturing processes, contributions of PSE such as process modelling, automation and control, supply chain and logistic

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optimisation and life cycle assessment, and finally highlight the challenges in the lens manufacturing industry are given.

LENS MANUFACTURING PROCESS

In order to describe the photographic lens manufacturing process, several literature reviews were done from both scientific sources as well as commercial websites of lens manufacturers. In general, the overall production process comprise of i) materials acquisition, selection and processing, ii) machining, iii) finishing, and iv) final assembly. The details are explained in the following sub-sections.

Materials Acquisition, Selection and Processing

Optical glasses for photographic lenses are made from combined materials such as silicon dioxide (SiO_2), sodium carbonate (Na_2CO_3), calcium oxide (CaO), lead oxide (PbO), potassium oxide (K_2O) and barium oxide (BaO), calcium fluoride (CaF_2), and rare earth materials such as lanthanum [2, 4]. They were mined naturally or produced synthetically in the factories. Selection of these materials with the combined percentages are the proprietary of lens manufacturers, but in general will be based on refractive index and Abbe's number [2]. The index of refraction of a selected material will determine the light passage angle to the medium, which it is desired to be low. The high Abbe's number will indicate low dispersion glass, one of important qualities for avoiding chromatic aberration. Apart from glasses for the lens construction, it also has the barrel. This barrel will be using materials either from metals or plastics, or in combination. Common types of metal include aluminium, titanium, or stainless steel. For lens barrel made from plastic, it will use acrylonitrile butadiene styrene (ABS) or polycarbonate [4].

After determining the expected optical qualities of a lens, the selected lens materials in their grainy powder form will be mixed together in a mixer. Oxygen, iron and other impurities are removed physically or chemically to reduce light transmittance inside the glass. At high temperature which is the melting point of the materials, the mixture is heated, fused, homogenized, shaped and cooled. Here, controlling the temperature and fusing/cooling processes are critical for the production of superior lens glass [2], along with defects inspections.

Lens Machining

In this step, the cooled glass crystal for a specified raw shape and thickness will undergo two stages of grinding and polishing methods [2, 5]. The first one called as rough grinding, which to polish pre-pressed glass to form a desired lens shape with an approximate curvature radius and core thickness [4]. The machine for this purpose is equipped with ultra-hard grindstones which also to remove defects and irregularities on the glass surface. Among parameters that must be controlled optimally are rotation speed, thickness and grinder angle. Next is the stage of precision binding as to improve spherical accuracy and transparency of lens with the use of diamond grains [6] has studied high efficiency ultra-precision grinding for large aperture glass by cross grinding and has analysed grinding conditions experimentally to get optimum balance between high efficiency and high surface quality. Furthermore, [7] has showed that chemical action-assisted ultra-precision grinding using La-doped CeO_2 slurry resulted in five times higher productivity rate with a polish-free fine surface than conventional grinding. The next major step in this lens machining is polishing for finalizing the appearance and performance related to its curvature. Lenses are polished until the surface roughness has been reduced to characteristic length at sub-micron level [2]. Constant flow of lubricant such as is required to cool down the heat generated from friction. The other side of the lens surface to be polished will be covered by protective film as to avoid damages and flaws [5]. The polished lens will then be cleaned and washed using chemicals, detergent, pure water and alcohols to take off the protective film, and to remove any dirt and debris. Inspections for spherical surface precision, core thickness and exterior precision will be performed the lens enters the next stage. These inspections will utilize both visual examination and specialized instruments. For example, spherical surface precision is visualized to examine the Newton's Ring, while thickness will be determined using a precision instrument that use lasers.

Finishing

After passing inspection from the previous stage, lens must be centred in the process called as centring. The centring is responsible to ensure the optical axis and the mechanical axis to become completely circular [2, 5]. Optical axis of the lens is related to the core part while mechanical axis is for the outer cylindrical edge. The difference between these two axes is referred as lens de-centration or axial displacement centering error [2].

After the centering process, batches of lenses will undergo for another cycle of cleaning that thoroughly wash in an ultrasonic and vacuum system. This is important to ensure the remaining fine dusts no hot stick on the glass surfaces when compounding and coating processes are performed. Compounding process is an application of liquefied resin on the aspherical lens surface, that can effectively eliminate or correct spherical aberrations and distortions [5]. Examples of these resins are UV-curing ones such as polytetrafluoroethylene, polybenzyl methacrylate and polydiallyl phthalate, and are heat-curing ones such as TB2960 and TB2960B [8]. The coating process involves the application of thin layers of chemicals and metal derivatives compound to the surface of the lens by vacuum deposition. Innovations are concentrated in this coating technology for many lens and camera makers as to find the best coating outcomes. Nikon has developed and applied nanocrystal coat that reduce significantly reflection of light which otherwise can cause ghost and flare [9]. Besides, the company also utilize fluorine as a coat to repel dust, water droplets, grease and dirt for easy wiping. Should dust and moisture are not repelled or removed, they will be a perfect starting medium for fungal growth on the lens surface, which will later deteriorate the expected optical qualities. Both magnesium fluoride and calcium fluoride are typical coating chemicals and considered as anti-reflection.

Final Assembly

After application of protective coatings, various glass lenses are assembled together to form a complete lens unit, housed by a lens barrel. All individuals such as anti-reflection (AR) glass, extra low dispersion (ED) glass, aspherical glass, ED aspherical glass, vibration reduction or image stabilization elements are aligned and grouped depending to the specific purpose of the built lens. Lens, metal and plastic are assembled manually with utmost care to produce a lens system. Furthermore, incorporations of lens diaphragm, focusing indicator, focusing motor, focusing rings, image stabilization components, and electronic circuits to the lens system are done prior to final inspection, packaging and distribution. Optical and electronic components of the photographic lens are comprehensively inspected for performance and for the existence of optical deformities including intra-barrel dust and other debris [2].

PSE CONTRIBUION IN SUSTAINABLE LENS PRODUCTION

The concept of sustainable production or manufacturing is becoming increasingly mature due to the focus on many of its research topics for a long time [10]. Pillars for sustainability are economy, society and environment. The relationship between PSE and sustainability and how the former contributes in achieving the latter can be found in many literatures, among them are from [11-13]. Considering many stages involve in producing photographic lens, starting from materials selection and processing until lens packaging and distribution, the role of PSE is unanimously important for sustainable production. In addition, those stages demonstrate symbiotic job-doings between personnel and machine in order to achieve precision, perfection and product quality assurance. In the material mining and extractions for lens and barrel productions, environmental impact assessment and life cycle assessment are PSE integral and standard procedures required by acts and regulations.

Furthermore, mineral resources that are mined and traded in conflict-affected and high-risk areas, may become a source of human rights abuses that include child labor and forced labor, or a source of environmental destruction, conflict, and social injustice. In this regard, Nikon Corporation has applied their internal Responsible Minerals Sourcing Policy as an action to ensure socioeconomic and environmental attributes are preserved [14]. For the similar purpose, another lens maker, Panasonic Corporation exercised the Responsible Supply Chain to promote responsible procurement of minerals in its global supplies [15]. Next, PSE contribution in the area of material selection and processing can be realized by the applications of computer aided tools for molecular designs and flowsheet constructions [16-17]. Optimal selection of functional materials for correcting lens aberration and anti-reflection properties, is requiring systematic methods on top of the traditional PSE approaches for optimal design, synthesis and control of macroscale manufacturing processes. For example, Canon Corporation has developed ultra-low dispersion glass materials that has similar characteristic to fluorite. In the area of lens machining that involve grinding and polishing, PSE's automation and control play crucial roles. Olympus Corporation has shown examples in this area where technologies replaced skills. Automated system for grinding and polishing steps together with their independent developed grindstones have enabled them to achieve quality, cost and delivery (QCD) targets [18]. Last but least, PSE areas of modelling and optimization for the product logistic and distribution have also applied. Like any produced good, the photographic lenses undergo the same logistic objectives which are to ensure products safely reach customer's site with correct amount, at a given time with minimum cost. Many works in the area for modelling and optimal supply chain of produced products can be found among them from [19-20].

CHALLENGES

As highlighted by [21], the mayor challenges towards PSE implementations are process and product design, process control, R&D and process operations, modelling, integration, and supporting methods and tools. Specifically for the photographic lenses production, challenges can be derived from [21] which include product design, automation and control, as well as to comply with sustainable production targets. Realizing constant requirements to continuously improve optical qualities, both academia and industry need to collaborate in the area of functional material design and production, for example meta-lenses material which can perfectly remove spherical aberration [22]. This is regarded as the next generation lenses which synthetically produced for improving qualities and reducing over reliance onto lens materials that are found naturally. In the aspect of automation control, the constant challenges of replacing skilled workers with automated technology with the aims to accelerates the evolution and differentiation of technology [18]. Precision requirements in lens grinding, polishing and visual inspection have been the sanctuary of highly skilled craftsmen. The challenges include to mimic manual operations by knowledge and techniques of skilled workers with automated and controlled machines and instruments for mass productions, stable quality and lower costs. More R&D works and mutual collaborations are essential in the future.

For achieving sustainable lens productions, some industry players have implemented exemplary actions, as reported in [14-15]. Others are included in the annual sustainability reports that can easily accessed from internet for public references such as [23-25]. As sustainability agenda is ongoing and cumulative efforts, lens makers must continuously demonstrate their management and operational wills especially for energy and materials conservations as well as avoiding any damage to the environment in every element in the whole value chain operations.

CONCLUSION

The review for proses systems engineering (PSE) in photographic lenses production with sustainable manner is the key content for this paper. PSE contributions either by the application of tools or approaches have been in the production stages, and will be further incorporated due to technological advancements and emerging requirements. The paper has highlighted detail photographic lens production steps that include material selection and processing, machining, finishing and assembly. Realizing these are important value chain, PSE has and will be playing significant roles should the mentioned challenges are to be solved. Concerted efforts from academia and industry are paramount and will be translating into actions in achieving sustainability goals for this industry.

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