THE IMPACT OF THE THICKNESS OF THE WALL OF OPTICAL LENSES ON THE STABILITY OF THEIR PRODUCTION PROCESS

MARTIN ŠINKORA[1], MIROSLAV ŽITNÁK[1], MAROŠ KORENKO[2] , TARAS SHCHUR[3],
YURIY GABRIEL[3],OLEXANDR PUSHKA[4].
SLOVAK UNIVERSITY OF AGRICULTURE IN NITRA,
FACULTY OF ENGINEERING, NITRA, SLOVAKIA
[1]DEPARTMENT OF BUILDING EQUIPMENT AND TECHNOLOGY SAFETY,
[2] DEPARTMENT OF QUALITY AND ENGINEERING TECHNOLOGIES
[3]LVIV NATIONAL AGRARIAN UNIVERSITY, UKRAINE
FACULTY OF MECHANICS AND ENERGY
DEPARTMENT OF CARS AND TRACTORS,
[4]UMAN NATIONAL UNIVERSITY OF HORTICULTURE,
DEPARTAMENT OF AGROENGINEERING

Abstract

The article compares the stability of the production process of two plastic optical lenses produced by the injection molding process. Moreover, it evaluates the effects caused by using very thick walls and very thin walls in plastic optical lenses. In our work, we compared lenses that differed only in the maximum wall thickness. In the experiments, we simulated the conditions of changing pressure and injection speed. The common process parameters that the organization uses by default were used as a basis. We changed the after-pressure and injection pressure to 102%, 105%, 98%, and 95% in the experiments. The results evaluate the proportion of non-conforming products (scrap) that appertain to each change in the parameters of production. From the results, we concluded that lenses with greater wall thickness have a narrower process window than thinner lenses. Based on these findings, we proposed the adoption of organizational measures in the production of plastic lenses.

Key words: process stability, injection molding, quality

1 Introduction

A high-pressure injection is standardly defined as "a method of forming plastic elements by heating the molding material to make it flowable and then injecting it into a mold" (Xie, Lei & Shen, Longjiang & Jiang, Bingyan, 2011, Merriam-Webster, 2020, ONEX Machinery. 2021). We divide the injection process itself into three fundamental stages. The first is the injection of plastic into the mold itself (filling). During this phase, 95% -99% of the cavity volume is filled. The second phase is the so-called after-pressure, where the remaining cavity spaces are filled, and the part reaches dimensional stability. The last stage is called cooling. During the final phase, the element solidifies and becomes dimensionally stable in lower temperatures.

A necessary condition for quality production is that the machine, in combination with the mold, can produce identical consecutive parts at set parameters. During injection, slight changes in injection parameters may occur due to random external influences. These influences include the change in ambient air temperature, voltage fluctuations in the electrical system, machine vibrations, imperfect homogeneity of the material used, and the like.

Process stability is the ability of a machine and a mold to produce identical parts in a row under the influence of random external impacts. This stability can be tested by intentionally changing some process parameters (such as material temperature or injection pressure) by small values and monitoring whether we can still produce identical parts. If so, the process is stable even if the parameters change randomly by some percentage value (most often 2%, 5%, and so forth). The range of process parameters at which the machine can produce suitable parts is called the process window (Rosato, 2004, Resinex. 2021).

Optical lenses are used in automotive applications in combination with LED bulbs. An LED bulb, or more commonly a set of bulbs, acts as a light source. The optical lens then collects the light produced by these LEDs and changes its direction to achieve the desired light distribution (Auer-lighting, 2021). We achieve these properties by using a specific lens geometry. The side from which the light enters must be straight and smooth, while the side from which the light concentrates and where it emits has the shape of a spherical lens.

The desired curvature and size of the lens itself (height and width) then results in the determined lens thickness. From the point of view of the production of plastic parts, this shape requirement is the main complication due to the manufacturing errors known as sink marks and bubble formation. When designing plastic parts, we try to avoid excessive concentrations of material. On the contrary, when designing optical lenses, the concentration of material is necessary (Autodesk, 2016, Simcon. 2020, Sinomould. 2021).

There are several ways to solve this problem. All of them are commonly applied simultaneously. They support each other in their benefits but unfortunately also in their negatives. From the injection molding process point of view, we can solve sinking material by prolonging the after-pressure time and the cooling time. The reason is to ensure the consolidation of dimensions during the after-pressure. Subsequently, a gradual equalization of temperatures in the total volume of the lens is achieved by extended cooling. Otherwise, deformations would occur after removing the part from the mold.

Modifications to the mold can also achieve some improvement in this condition. The first step is to expand the cross-section of the inlet channel gate. The pressure is transmitted to the cavity through this cross-section. Its enlargement ensures a more even distribution of the pressure in the entire volume of the part. Another way to facilitate production is to guarantee optimal cooling of the cavity. We can achieve this by placing the cavity away from the hot runner system so that the cooling can be evenly distributed around each side of the part. The last way to solve the problem of collapse is to create a counter-deformation in the mold. That is to enlarge the cavity so that the lens sinks into the desired shape.

The work aims to prove the dependence between the thickness of the optical lens and the stability of the injection process.

While waste percentage, cycle time, and other parameters are considered and quantified at the design stage of the optical lens, process stability has not yet been quantified. If we prove the dependence between the above-mentioned phenomena, it will allow us to predict the process stability of new lens designs more precisely.

2 Material a methods

2.1. The selection of the monitored parts.

When choosing lenses, we tried to find ones that will be as identical as possible in all properties except wall thickness. Subsequently, we performed measurements that simulated random fluctuations in the specified process parameters and compared how the share of non-conforming products in total production changes based on these changes.

We marked the selected lenses as "lens A" - thick-walled lens and "lens B" - thin-walled lens. Both are made of PMMA type material, specific trade name:

Plexi 8N SuPure clear.

Lenses A and B have the characteristics listed in Table 1.

Table 1 Properties of selected optical lenses A and B

	Surface area (cm^2)	Volume (cm^3)	Surface treatment	Use in the light	The inlet type	Number of cavities in the form	Used injection molding machine	The largest wall thickness (mm)
A	36,6	6,2	High Gloss	High Beam Lens	Film	4	Engel victory 80t	12,39
B	37,5	4,8	High Gloss	High Beam Lens	Film	4	Engel victory 50t	3,88

2.2. Experimental conditions

The first condition in an experiment examining stability and the process window was to ensure that the process ran as it standardly does before it was subjected to an experiment. In the case of both lenses, we determined whether it was normal production based on long-term observation of the share of non-conforming products in the total production. If the observed percentage of non-conforming products was close to the long-term average of non-conforming products before the start of the experiment, we could say that the process was running normally.

The mold for the production of lenses A has been producing lenses since the beginning of 2021 on the injection molding machine No. 49 (Engel victory 80T) a total of five times. Table 2 shows the production process and the proportion of non-conforming products in individual productions.

Table 2 Production of lenses A from the beginning of 2021

Production number	1	2	3	4	5	Total
Date	9-14.01.	21-25.01.	29-03.02	16-18.02.	1.-10.03.	
Number of pieces produced	7000	2720	5556	4108	7409	26793
Non-conforming products, pcs	356	128	96	276	483	1339
Non-conforming products, %	5,086	4,706	1,728	6,719	6,519	4,998

We used a 50% mean interval to determine the range of non-conforming products at which the production standardly occurs. The value of the interval is 2.495, which implies that if the share of waste in the production is in the range from 2.503% to 7.493%, we can consider this production as normal.

The mold for the production of lenses B has been producing lenses from the beginning of 2021 on the injection molding machine No. 53 (Engel victory 50T) four times in total. Table 3 displays the course of production and the share of non-conforming products in individual productions.

Tab. 3 Production of lenses B from the beginning of 2021

Production number	1	2	4	5	Total
Date	13-16.01.	24-28.01.	12-15.02.	1-8.03.	
Number of pieces produced	4867	5209	3600	10500	24176
Non-conforming products, pcs	74	103	41	188	406
Non-conforming products, %	1,520	1,977	1,139	1,790	1,679

We applied the same mean interval. It will have a value of 0.419% for lens B. That denotes that if the share of waste in production is in the range of 1.260% to 2.098%, we can consider this production normal.

To determine the stability of the process and compare the results, we performed four identical interventions in the process for both lenses.

In Experiment 1, we set the after-pressure and injection pressure to 102% of the value specified in the mold datasheet.

In Experiment 2, we set these values to 105%.

In Experiment 3, we set the values in the opposite direction to 98%.

In the last experiment 4, we set both values to 95%.

During each experiment, we made 10 sets of lenses. Both molds for lens A and B have four cavities. Hence, we had 40 parts to evaluate one experiment. The parts were evaluated visually.

3 Results and discussion

Lens A experiments

Lens A experiments took place on 13th of March from 11:00 to 13:45. From the start of the shift at 6:00, the injection molding machine produced 72 sets of optical lenses (288 pieces). Fifteen of these were unsatisfactory. There were 5.208% of non-conforming products, which at intervals implies normal production. We performed all experiments without interrupting production. The results are captured in Table 4.

Table 4 Results of optical lens A experiments

Experiment number	1. (102%)	2. (105%)	3. (98%)	4. (95%)
Number of pieces	40	40	40	40

produced				
Non-conforming products, pcs	1	17	4	11
Non-conforming products, %	2,5	42,5	10	27,5

In the first experiment, with an after-pressure and injection pressure of 102%, we observed only one piece of the lens, which was marked as a non-conforming product. Figure 1 presents a line passing through the middle part of the slide. The non-conforming product came from cavity number 2.

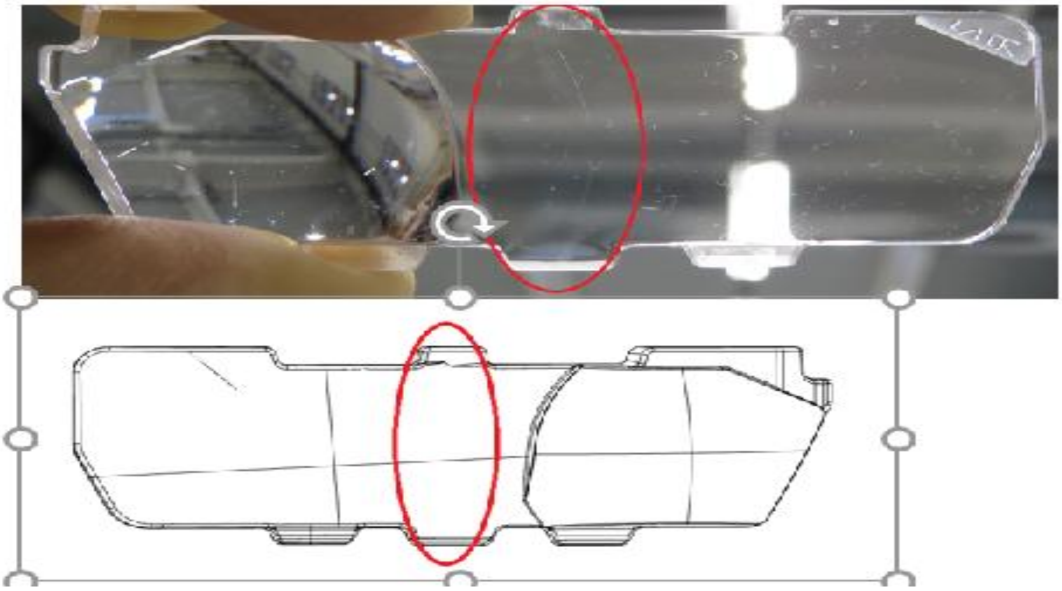

Figure 1 Scratch in the middle of the slide

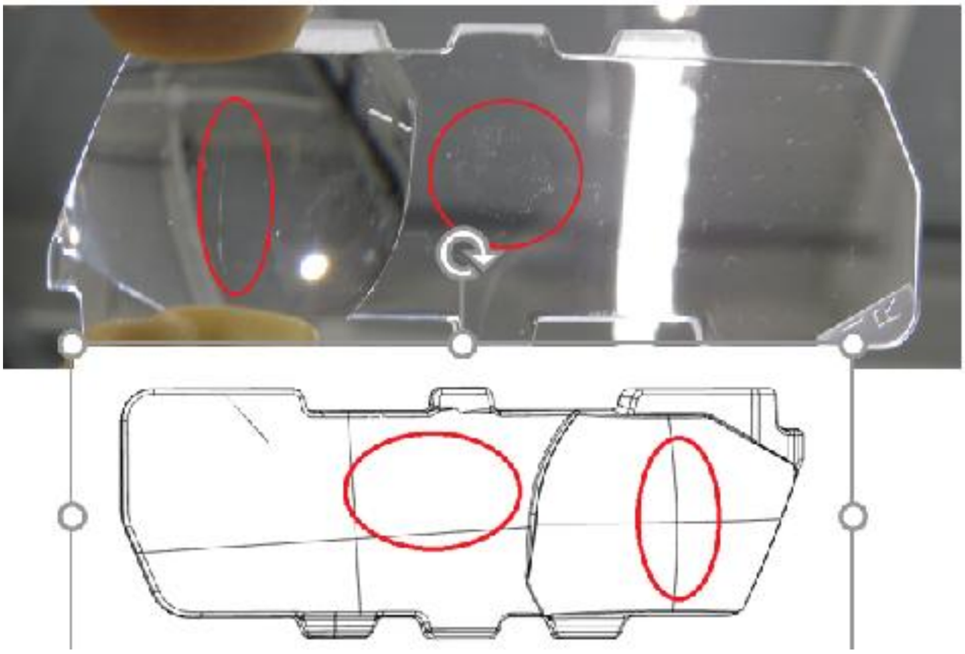

Figure 2 Scratch in the lens area

In the second experiment with values of 105%, we observed substantial errors on the entire surface of the produced lenses. Although the increased pressure did not change the dimensional properties of the part, it resulted in the formation of additional scratches and creep marks on the surface of the produced lenses. Six of these scratches were very similar to those shown in Figure 1. Another seven parts were marked as non-conforming products due to scratches in the lens area. That is illustrated in Figure 2. Figure 3 pictures a combination of scratches and creep marks. We noticed that in four cases.

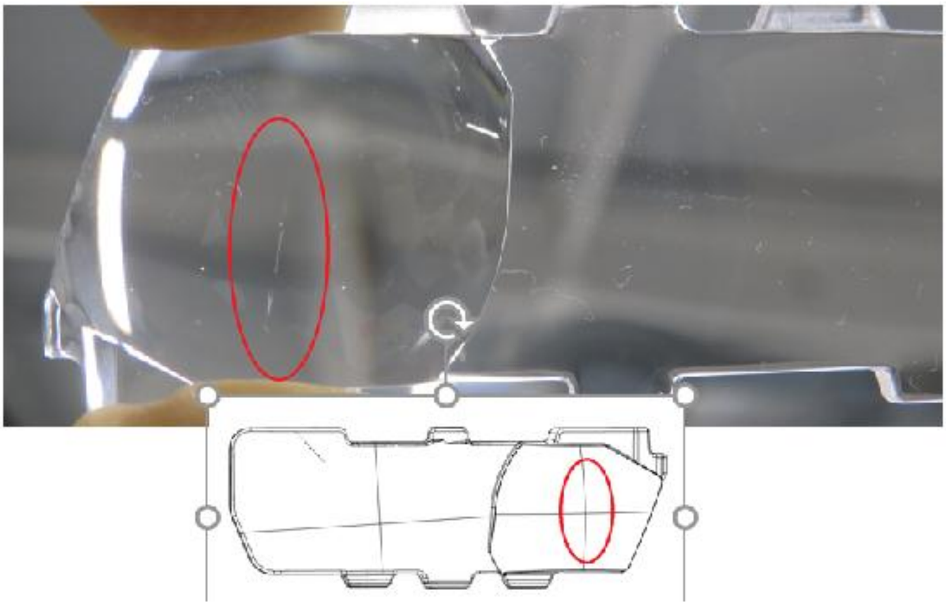

Figure 3 Scratch in the lens area and creep in the slide area

Cavity number 2 in the mold was most affected by the change in pressure. During experiment 2, all lenses produced by it showed the scratches shown in Figures 1 and 2. Other non-conforming products were formed relatively evenly in the other cavities. The distribution of non-conforming products in the cavities was K1 = 3, K2 = 10, K3 = 2, K4 = 2.

In the third experiment, we observed two identical scratches and creep marks as in Figure 3. Both are manifested in Cavity 3. In Cavity 2, we did not observe any scratches as we saw in Experiment 2. However, two scratches of the type we see in Figure 4 appeared.

In the last experiment, one scratch of Figure 4 appeared in cavity number 2. However, a new problem has arisen with sink marks in the lens area. We tried to capture the sink marks in Figure 5. Due to the great difficulty of photographing the sink marks of a transparent part, the error in the image is not very visible. The distribution of sink marks in the cavities was K1 = 4, K2 = 2, K3 = 4, K4 = 2.

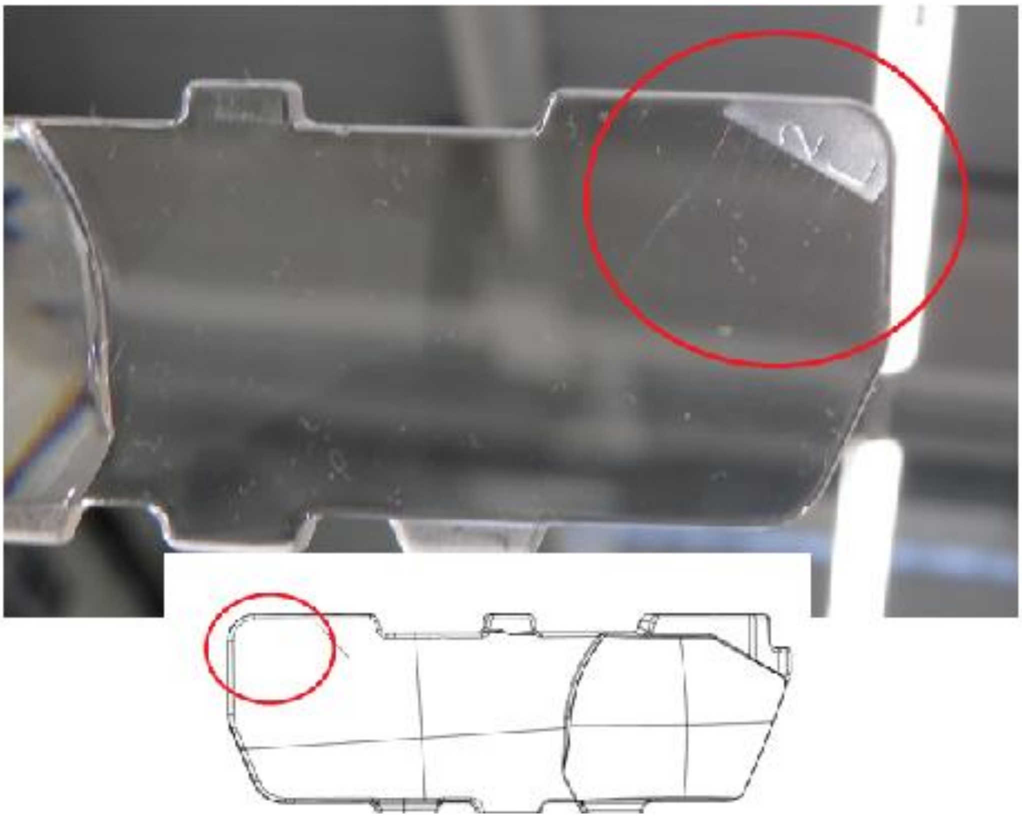

Figure 4 Scratches in the upper right corner of the slide

Figure 5 Depression in the lens area

After the end of the experiments, the mold continued production during the next shift with the setting of nominal parameters at the level of 100%. By the end of the shift, the number of non-conforming products had reached 4.860%.

Lens B experiments

Lens B experiments took place on 26.03. from 9:00 to 10:15. From the start of the shift at 6:00, the injection molding machine produced 55 sets of optical lenses, which means 220 pieces. Seven pieces of these were unsatisfactory. Non-conforming products were at the level of 1.272%, which was in the interval indicating normal production. We performed all experiments without interrupting production. The results are pictured in Table 6.

Table 6 Results of experiments on the optical lens B

Experiment number	1. (102%)	2. (105%)	3. (98%)	4. (95%)
Number of pieces produced	40	40	40	40
Non-conforming products, pcs	1	4	0	1
Non-conforming products, %	2,5	10	0	2,5

In the first experiment, we observed one piece where a scratch appeared in the corner of the lens 1 of cavity 1.

In the second experiment, the number of defects in the corner increased. All occurred on cavity 1 in the lower-left corner. In all these cases, it was a variant of the scratch shown in Figure 6.

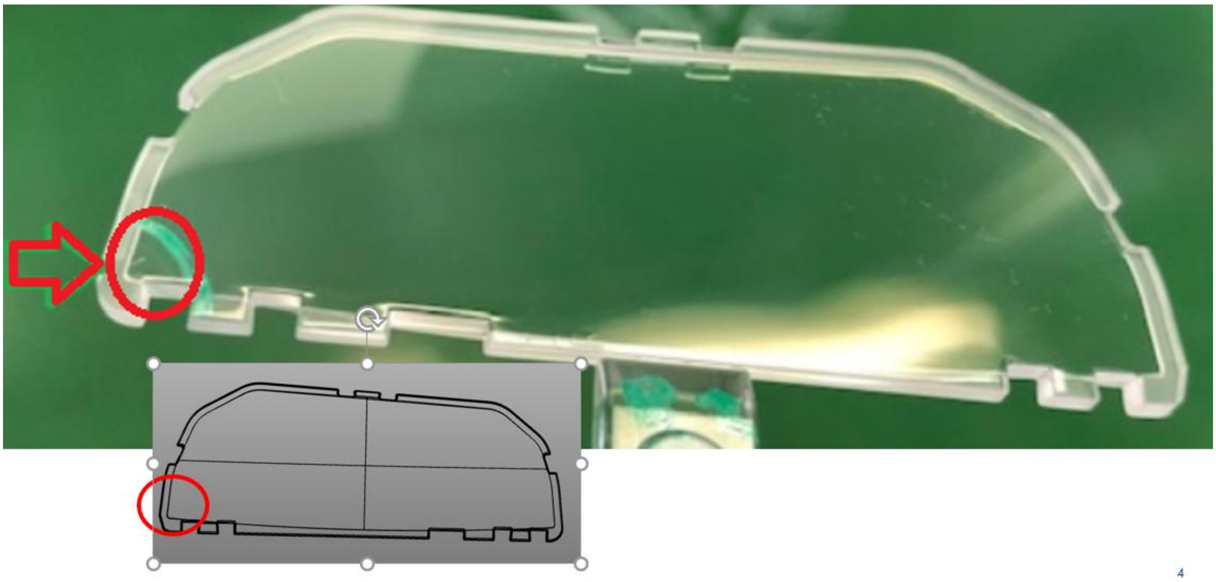

Figure 6 Scratch in the corner of the part in the cavity 1

In the third experiment, we did not notice any lenses with defects.

In the fourth experiment, we recorded one lens with a defect. Initially, we did not notice it at all, and we only discovered it during the transillumination test. The only way to photograph it was against a window, as seen in Figure 7. This part came from cavity 4.

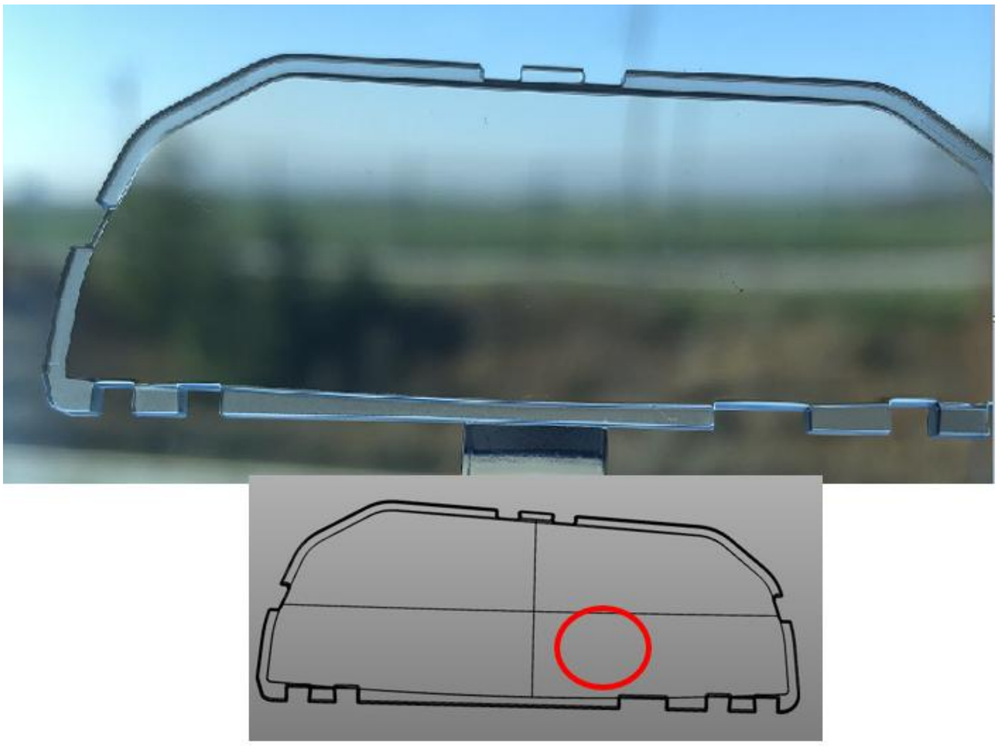

Figure 7 Scratch the centre of the lens

Most scratches occurred at the edges of the lenses, where the greater wall thickness changed to a smaller one. That is because, during the process of filling the cavity with material, these edge areas tend to be filled last. For the material to reach these areas, it is under increasing pressure. The scratch is then due to the material being pressed too hard against the steel. In the case of scratches in the edge areas close to the parting plane, these are demolding scratches, where the edge of the parting plane scratches the parts during demolding (Plainis, S et al. 2006, Ecomolding, 2019). In the case of scratches in the middle of the lens, this is a similar principle, where the lens is scratched as a result of "sticking" to the cavity.

The second observed phenomenon was an increased incidence of defects in certain cavities compared to others. In the case of lens A, it was cavity 2. In the case of lens B, five of the six scratches were observed in cavity 1. That may be due to uneven material distribution. The inlet channel is usually centred so that the flow of material from the nozzle is distributed evenly among all cavities. However, due to inaccuracies in production, it is practically impossible to tune it so that the distribution is perfectly accurate. Such inaccuracies lead to instability of the laminar flow of plastic in the switchboard. (Bozzeli J. 2011, Yadav A. 2013) Therefore, one cavity is always filled a little earlier than the others. If it is possible to adjust the process by adjusting the injection parameters so that the total waste is not high, that is fine. However, such inaccuracies contribute to lowered process stability.

4 Conclusion

The work aimed to compare the stability of the process for two types of optical lenses, depending on their thickness.

A large part of the scratches and optical defects occurred in lens A in the side area. Thus, outside the zone with the greatest wall thickness. We assumed that this was due to the steep transition in wall thickness between the two zones. That resulted in the pressure acting through the lens on the already solidified wall of the side and forming cracks. In cavity 2, where the most substantial number of errors occurred, there may also be a problem with unbalanced filling. If the first is filled, the injection pressure here will cause a higher material flow rate than in other cavities, resulting in traces of creep. Of course, we can expect these defects in the design of this lens. The normal waste of this lens is also greater than with thin-walled lenses.

In the case of optical lens B, greater process stability was confirmed. The total value of non-conforming products during the four experiments reached 3.75%, which is only slightly higher than the normal waste on this lens. There was also a problem with unbalanced filling, with five of the six non-conforming products coming from cavity 1 of this mold. Due to the better design of this lens in terms of material injection, the shape of this lens was able to produce in a more stable process compared to lens A.

We can state that we managed to prove the connection between the thickness of the lens wall and the stability of the process. Although higher total waste is expected for thick-walled lenses, knowledge of the stability of the process in the production of lenses has not yet been accumulated. At the same time, they are a significant indicator for production planning. If we know that we can expect lower process stability based on the design for these types of lens, we can take measures to eliminate this risk and thus reduce the total waste and other negative impacts on production.

These measures may include preventive tuning of the mold for multiple IMM machines in case the injection machine needs to be changed. Preferably placing such lenses on newer injection molding machines where parameters are less likely to fluctuate and avoiding moving such molds to injection machines for which they have not been tuning unless necessary.

In further investigating the stability of the process, it would be the best course of action to perform similar experiments on several pairs of lenses and quantify from this database how much the stability of the process decreases as the maximum wall thickness increases. This parameter could be included in the lens cost calculation phase.

5 Bibliography

1. Aure-Lighting. 2021. LED Lenses [online]. © 2021 [cit. 2021-03-14]. Retrieved from: https://www.auer-lighting.com/en/products/lenses/led-lense
2. Autodesk. 2016. Missing the Mark: How to avoid or camouflage marks in injection-molded parts. In *Resource Center* [online], pp. 1-6 [cit. 2021-03-15]. Retrieved from: https://damassets.autodesk.net/content/dam/autodesk/www/mech-eng-ressource-center/cae-analyst/assets/fy17-mold-engineer-sink-marks-report-en.pdf
3. Bozzelli J. 2011. Why Multi-Cavity Molds Fill Unevenly. [online]. [cit. 2021-05-09]. Retrieved from: https://www.ptonline.com/articles/why-multi-cavity-molds-fill-unevenly
4. Ecomolding. 2019. What causes scratches in injection molding products. [online]. [cit. 2021-05-09]. Retrieved from: https://www.ecomolding.com/scratches/

5. Merriam-Webster, “Injection molding.” *Merriam-Webster.com* Dictionary, https://www.merriam-webster.com/dictionary/injection%20molding, [cit. 2021-02-27].
6. ONEX Machinery. 2021. What Are the Important Parameters of the Injection Molding Process?. [online]. © 2021 [cit. 2021-03-17]. Dostupné na: https://onexlimited.com/%e2%85%b0-what-are-the-important-parameters-of-the-injection-molding-process/
7. Plainis, S et al. 2006. Road traffic casualties: understanding the night-time death toll. In Injury prevention : journal of the International Society for Child and Adolescent. vol. 12(2). s. 125-128. [online]. [cit. 2021-03-14]. dostupné na : https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2564438/
8. Plasty Gabriel. 2020. Konštrukcia a výroba šošoviek pre LED svetlomety z plastu namiesot skla. [online]. [cit. 2021-05-09]. Dostupné na:https://www.plasticportal.sk/sk/konstrukcia-a-vyroba-sosoviek-pre-led-svetlomety-z-plastu-namiesto-skla.html/c/6647/
9. Pačaiová, H., & Ižaríková, G. (2019). Base Principles and Practices for Implementation of Total Productive Maintenance in Automotive Industry. *Quality Innovation Prosperity*, *23*(1), 45–59. https://doi.org/10.12776/qip.v23i1.1203
10. Pačaiová, H.; Andrejiová, M.; Balažiková, M.; Tomašková, M.; Gazda, T.; Chomová, K.; Hijj, J.; Salaj, L. Methodology for Complex Efficiency Evaluation of Machinery Safety Measures in a Production Organization. Appl. Sci. 2021, 11, 453. https://doi.org/10.3390/app11010453
11. Resinex. 2021. PMMA Altuglas. [online]. [cit. 2021-04-29]. Dostupné na: https://www.resinex.cz/produkty/altuglas.html
12. Rosato V. Dominick – Rosato V. Donald - Rosato V. Matthew. 2004. Plastic Product Material and Process Selection Handbook. [online]. Elsevier Science. [cit. 2021-03-14]. 618 s. ISBN 978-1-85617-431-2. Retrieved from: https://doi.org/10.1016/B978-1-85617-431-2.X5000-2
13. Silver Optics. 2020. About us. [online]. [cit. 2020-09-15]. Dostupné na: http://www.opticslenschina.com/
14. Simcon. 2020. Project OptiSys: Plastic instead of glass - we collaborated with partners including KraussMaffei, Hella and Fraunhofer, to create new multi-layered lenses for LED headlights. [online]. [cit. 2021-05-09]. Dostupné na: https://www.simcon.com/project-optisys-plastic-instead-of-glass
15. Sinomould. 2021. Mould Parts Function. [online]. © 2021 [cit. 2021-01-15]. Dostupné na: https://www.sinomould.com/Mould-part-function.html
16. Xie, Lei & Shen, Longjiang & Jiang, Bingyan. (2011). Modelling and Simulation for Micro Injection Molding Process. [online]. IntechOpen. [cit. 2021-01-10]. DOI 10.5772/16283. Dostupné na: https://www.intechopen.com/books/computational-fluid-dynamics-technologies-and-applications/modelling-and-simulation-for-micro-injection-molding-process
17. Yadav A. 2013. Subject study of operation and maintenance of all electric injection moulding machine. [online]. © 2021 [cit. 2021-03-17]. Dostupné na: https://www.slideshare.net/anymona1991/seminar-on-all-electrical-injection-moulding-machine-main