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Influence of thermal ageing on the fracture and lifetime of additively manufactured mold inserts

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Abstract

Due to the significant technical benefits of additive manufacturing (AM), its application has grown considerably in recent years. In this respect, the integration of AM in the injection molding (IM) process chain for tooling purposes is an ongoing research topic. In the current study, the design, fabrication and use of a tool inserts for injection molding process fabricated by a vat photopolymerisation technique. Since molds during the injection molding process are subjected to cyclic thermal variation, accelerated thermal ageing was applied on the AM mold inserts to emulate the effect of continuous production on the tool lifetime. The additively manufactured mold inserts were exposed to thermal cycling loading in the range between room temperature up to 100 °C, and then, they were used in the actual injection molding process. According to the obtained results, effects of thermal ageing on behavior of the mold inserts are demonstrated. Moreover, fractographic analysis is performed on the fractured surfaces to determine crack initiation and propagation on the mold inserts. The current study provides insight about ageing and fracture of IM mold inserts produced by vat photopolymerisation, and these results can be used for the development of computational models, future material design and load-carrying capabilities of additively manufactured mold inserts to expand the use of AM for tooling purposes.

Key words: Additive manufacturing; Injection molding; Thermal ageing; Mechanical fracture; Soft tooling

1. Introduction

The progress in production processes can be considered as a main part of technical innovations. In this context, new methods are continuously introduced to answer the engineering demands. Additive manufacturing (AM) techniques along with advanced material development have been used for a wide range of applications [1,2]. It produces 3D haptic physical models layer by layer based on CAD models [3] and has attracted interest in several industries in their path toward digitalization of their manufacturing operations (Industry 4.0) due to its effectiveness in production of complex components in a shorter time compared with conventional processes. It is a reliable, efficient and cost-effective technique, which can revolutionize the manufacturing industry. Since applications of AM technique are considerably increasing across several industries (aerospace, biomedical, tooling, etc.), different aspects of engineering have been studied in this manufacturing process [4–8]. In recent years, product complexity and multi-functionality significantly increased, particularly in the plastics industry, and 3D printing has been utilized for fabrication of molds and inserts for injection molding (IM) manufacturing process for both soft and hard tooling [9,10,16] in response to these demands. In [10] the manufacturing steps for the production of 3D printed mold are described. Researchers utilized the AM technique to produce a mold with mirror-like surfaces, and then measured the hardness. By the obtained results, the researchers reported high capabilities of AM technique in producing optical quality molds with reduced process time. Injection molding is a manufacturing process for a wide range of products. Molds are essential elements in this cyclic process and the mold design must be specific for each product. During the IM process, the mold might
encounter different faults, which interrupt the part production. In injection molding, molds are traditionally fabricated by material removal processes (e.g. milling, grinding, electrical discharge machining, etc.). Advance manufacturing represent a group of processes for the production of injection molding tool that is innovating tooling process chains. In [6,11] status and future perspectives of AM applications in molds design and fabrication was explained. A research discussed rapid tooling techniques based on AM, with plastic inserts [12]. Furthermore, they reviewed cooling systems based on AM and their performance in improving mold cooling efficiency, which finally leads to reduction of molding cycle in production time.

Different aspects of mold fabrication by AM technique have been investigated by various researchers [13–16]. For instance, in prior investigation by the authors [14] AM was used to fabricate micro injection molding inserts with different types of geometric features. After fabrication of the mold inserts, they were used in a series of experiment and their durability and wearing were investigated. Moreover, the influence of the IM process parameters were investigated by means of measurements of different features on the molded parts. In another work [15] a 3D printed tool design was considered for the optimization of its cooling channels. Since 3D printing provides greater geometric freedom, a more desirable cooling system of the mold can be achieved. In this respect, the researchers developed a numerical model of the mold that was then validated by physical experiments. Product development in injection molding by AM molding tools is also an ongoing research topic [17]. Advance manufacturing has been used to produce injection molded parts for extensive functionality tests of the parts produced with the actual material of the final product. For this purpose, several design improvements and modification can be applied in the mold whose production and overall lead-time are drastically reduced by using AM methods. It should be noted that the soft tooling method (i.e. the production of tool insert by polymer AM rather than using metal AM, also known as AM hard tooling, according to the definition given in [18] (see Fig. 1) could be used for several thousand injection molding cycles [19]. The mold inserts fabricated by AM are suitable for intermediate production volumes in injection molding process and a relative economic advantage in comparison with conventional tooling can be achieved in selected conditions [20].

Since molds experience various conditions during their service life, investigations of these working conditions are necessary in order to determine the behavior of the molds in production and predict their performance. Various experimental studies have been conducted to determine the effect of environmental conditions on different engineering components [21–25]. For instance, behavior of bio-composite under accelerated thermal aging was investigated in [24]. To do so, the researchers fabricated exposed to various temperatures bio-composites, then characterized by tensile and flexural tests after a certain time of exposure. Recently, another study [26] investigated the influences of accelerated ageing on mechanical properties of polymeric composites. In this regard, the papered E-glass fiber reinforced plastic parts was exposed to elevated temperature, and three point bending tests and dynamic mechanical analysis were used for evaluation of ageing effects on material behavior. Two creep functions (limited time scale and wider time scale) and physical aging of injection molded glass fiber reinforced polypropylene was investigated [27] revealing a critical difference between modeling injection molded polypropylene and compression molded material.

In the current research, the AM technique is employed to produce IM inserts. Then, the fabricated molds inserts are aged, and all the specimens are utilized in the injection molding process. The behavior and performance of the tested molds are investigated and compared to determine influence of ageing on behavior of the insert under working conditions. Since the short-term accelerated aging is a good strategy for prediction of IM long-term behavior, the achieved results can be used not only for future material design, but also for the development of next computational models and load-carrying capabilities of mold inserts produced by AM technique.
Fig. 1. Tooling method fabrication flow charts.

Fig. 2. (a) mold inserts geometry (b) additively manufactured mold inserts.
2. Experimental setup and procedure

2.1. Design and manufacturing of mold inserts

In this work, a mask-projection based vat photopolymerization system, with bottom projection was used. The principle of this technology is that a liquid photopolymer resin in a vat with a transparent bottom and, by mask projection in the ultraviolet spectrum, parts are manufactured through selective photo-initiated crosslinking of the resin [28–30]. An industrial 3D-printing system was used with a 50 μm pixel resolution in X and Y directions, 50 μm layer thickness in Z direction and an accuracy of ± 50 μm in X, Y, and Z directions. The IM inserts were printed in the same time in one batch on the build plate (96 × 54 × 150 mm in the X/Y/Z directions respectively). The insert was fabricated with a methacrylic photopolymer material. The inserts design was selected based on previous research [6] and its geometry is shown in Fig. 2. The insert geometry is a 20 × 20 × 2.5 mm plate with two box structures having a 2 × 4 features pattern with 0.8 mm diameter cylindrical shape with 0.3 mm depth attached as well as two heart-shaped elements. In order to ease ejection of the IM parts a 2° draft angle was applied to the vertical walls.

The following step after printing is the post-processing, which has great influence on the final part geometry and strength. In this section, the insert strength can improve due to the crosslinking created by aging. Cleaning should be applied to the part that is covered with uncured polymer resin. A bath of isopropanol in a vibration plate ultrasonic cleaner bath was used to remove uncured resin. According to prior investigation [31] inserts were cleaned in diverse positions for removing the excess resin. The samples were dried and finally, post-cured to have no reactive resin remain in the parts with ultimate mechanical properties. The parts were exposed in a UV chamber with a diffuse UV light with an irradiant flux density of 300 W/m² for 30 min.

2.2. Injection molding process

An Arburg Allrounder 370A 600-70 Alldrive injection molding machine capable of a maximum clamping force of 600 KN and equipped with an 18 mm diameter reciprocating screw was used for the IM process. In the IM process two cavities (cavity one and three) were used with AM inserts for molding. Fig. 3(a) shows the setup and inserts placement and Fig. 3(b) presents the parts in both cavities. The process parameters for the experiments was selected according to the previous research for the tool life evaluation of photopolymer additively manufactured IM inserts in different IM conditions. The detail discussion about the contribution of parameters is given in [6]. Table 1 shows the selected IM parameters in the experiments. The total time for one IM cycle (and production of two parts) was 16 s. ABS Terluran GP-35 from INEOS Styrolution was used as IM material, processed at the melt temperature recommended by the material supplier between 220 and 260 °C. The natural ABS was mixed with a 2% weight ratio black master batch.

It is worth mentioning that all the molded specimens were produced with the same molding parameter settings to isolate the effect of thermal ageing from the influence of different manufacturing process conditions. After IM, the produced specimens utilized in this study were kept at room temperature for one month, and they were then classified as unaged specimens. Among those, several insert specimens were selected to experience accelerated ageing following the procedure explained in the next section.
3. Measurement and analysis procedure

The measurements were carried out with an Olympus Lext OLS 4100 laser scanning digital microscope equipped with a ×5 magnification lens. Similar measurement procedure to the previous study [6] carried out on the aged molded parts. The dimensions of five primary IM parts were measured in order to investigate the influence of thermal ageing on the features. Fig. 4 presents the acquisition of the heart shape on the IM samples for height and angle measurements. The height was measured with cross section profiles in three different locations along the heart shape. The results were analyzed by an image processing software (SPIP® from Image Metrology).

<table>
<thead>
<tr>
<th>Factors/unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>packing time/s</td>
<td>4</td>
</tr>
<tr>
<td>packing pressure/bar</td>
<td>200</td>
</tr>
<tr>
<td>Melt temperature/°C</td>
<td>260</td>
</tr>
<tr>
<td>Injection speed/ mm/s</td>
<td>40</td>
</tr>
<tr>
<td>Mold temperature/°C</td>
<td>25</td>
</tr>
<tr>
<td>Cooling time/s</td>
<td>5</td>
</tr>
</tbody>
</table>
Fig. 4. Acquisition of the heat features measurements (a) three cross section locations (b) lower angle shape of the heart measurement (c) height measurement.

4. Accelerated thermal ageing procedure

Since IM insert experiences high temperature in their life, investigations on the effects of working conditions on the behavior of molds is necessary. Indeed, molds manufacturer are increasingly being asked for assurance of the tools product lifetime, which may fail catastrophically in the process. Although the life expectancy of components in IM applications produced by conventional tooling technologies can be predicted from previous experiences, utilizing polymer material insert requires a profound new knowledge of the failure mechanism over several hundreds of molding cycles. Accelerated thermal ageing tests provides a reliable lifetime prediction without the need of performing expensive and time-consuming full-length molding trials. In this study, the working conditions of the insert are simulated and the related effects are examined by accelerated thermal ageing. To this aim, a Nabertherm chamber muffle furnaces with flap door (Muffle furnace L 9/14) was used. In order to avoid the rapid cooling of the specimens during the thermal loading, they are placed on a metal sheet inside the furnace. The ageing temperatures were 23 °C and 100 °C, both kept for 6 h. The temperature rate of change for heating and cooling was 5 °C/min. It should be mentioned that, as discussed in [32] for the polymeric materials, a common approach is to assume the rate of ageing is increased by a factor:

\[ f = 2^{\Delta T/10} \]  

where \( \Delta T = T - T_{\text{ref}} \), where \( T_{\text{ref}} \) is a reference temperature at which the influences of ageing are to be determined, and \( T \) is an elevated temperature used to accelerate these effects. Since the mold inserts experience both room and elevated temperature in their service life, 100 °C was selected as aging temperatures. Although there is a lack of standard conditions for investigation on accelerated weathering behavior of 3D printed components, it is commonly assumed that elevated temperature can be utilized as a method of accelerated ageing [28]. However, the smaller components are more sensitive to environmental attack compared to large components providing a more conservative estimate of environmental resistance. The specimens under accelerated aging and thermal ageing cycles are shown in Fig. 5. It should be noted that each specimen experienced 20 cycles of thermal ageing. After the aging, the specimens are cooled down to room temperature, kept for two weeks at room temperature and then utilized in the same way as the unaged specimens.

The mold inserts were weighted with an accuracy of ± 0.001 g before and after the accelerated thermal ageing. A calculation of mass loss in percent is obtained as follows:

\[ \Delta W = \left( \frac{W_A - W_0}{W_0} \right) \times 100 \]  

(2)
where \( W_0 \) and \( W_A \) are the original weight and the weight after aging values, respectively. The length, width and thickness of the inserts were measured before and after ageing. All the changes related to the weight are less than 1% after accelerated thermal ageing as shown in Table 2. Moreover, an optical microscopy assessment was conducted and no type of failure was observed on the aged specimens after thermal ageing.

![Fig. 5. Mold inserts in the heat chamber (left), and the applied cycles of accelerated ageing (right) each specimen experienced 20 cycles of thermal ageing.](image)

<table>
<thead>
<tr>
<th>Part number</th>
<th>Original weight (g)</th>
<th>Weight after ageing (g)</th>
<th>( \Delta W ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1542</td>
<td>1.1459</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>1.1449</td>
<td>1.1338</td>
<td>0.96</td>
</tr>
<tr>
<td>3</td>
<td>1.1538</td>
<td>1.1425</td>
<td>0.97</td>
</tr>
<tr>
<td>4</td>
<td>1.1175</td>
<td>1.1078</td>
<td>0.86</td>
</tr>
</tbody>
</table>

5. Results and fractographic analysis

The failure of an engineering component might be due to the environmental damage, or mechanical load [31]. In order to determine how and why the component fails, technical inspection of parts can provide crucial data. Indeed, by studying the fractured surface (fractography), it is possible to determine relation of the microstructures and main reasons of fracture. In this regard, fractography is one of the most valuable tools in failure analysis particularly focusing on crack initiation and propagation. In the current study, a focus variation Alicona Infinite Focus 3D microscope was used to investigate the surfaces of the aged and unaged inserts, and to perform the crack analysis. In order to track the surface of the mold inserts, the IM parts were collected and their surface measured to detect the cracks initiation and record the crack propagation through the mold inserts lifetime since the mold inserts themselves could not be directly observed during the IM process. The region of interest (i.e. the place on the inserts where are prone to the cracks) were selected according to previous experiments [6] and inspected with a \( \times 5 \) magnification lens. Apart from the location of cracks, the lifetime of the mold inserts were evaluated by the calculation of the crack propagation speed. The shot number at which the cracks started was recorded until critical failure of the mold inserts occurred. Table 3 presents the injection molding process parameters in normal and aged conditions and the number of shots the mold inserts withstand. In the IM experiments, the unaged inserts the cracks started after 90 shots from the corners of features. In the aged inserts, the maximum number of 50 shots were reached before cracks occurred on the mold inserts in test ‘Aged 1’, instead for the other three tests (i.e. ‘Aged 2’, ‘Aged 3’, ‘Aged 4’) the inserts withstand less shots.
By microscopic investigations on the surfaces of the final components, it was concluded that some cracks should exist in the mold inserts. Consequently, with an accurate optical investigation conducted on the surfaces of the inserts the cracks are recognized. In details, the first cracks are created after eight shots in aged inserts (test ‘Aged 3’). Not only the number of shots shows an important role in crack growth, but also accelerated thermal ageing play a crucial role in the speed of crack propagation. Fig. 6(a) and Fig. 4(b) show surface cracks after 70 and 30 shots in unaged and aged inserts respectively and the propagation of cracks with increasing number of shots. As expected, the crack growth in the aged inserts are higher compared to unaged inserts. This fact can be result of more micro-cracks due to the thermal ageing. However, applied thermal ageing accelerated crack-growth rates in the studied mold inserts. Since inserts fabrication and ageing process were identical for all the specimens, accuracy of this optical investigation was ensured. Crack branching observed in the aged mold, was associated with fast fracture, due to the release rate of stored energy in the material. This crack branching can also be the result of slow-moving fracture in presence of a complex stress field, like varying pressure loads and cyclic thermal conditions. Crack growth direction can be obtained from crack branching, and this recognition is beneficial in locating the section of mold, which contains the fracture origin. Fig. 6(f) illustrates the effect of cracks on the features after crack occurrence on the IM part (at the heart shape location) from left to right in perfect condition, propagated crack and the deformation of the features with the unaged and aged mold inserts respectively.

Table 3. Injection molding in normal and aged conditions.

<table>
<thead>
<tr>
<th>Test</th>
<th>Melt temp. [°C]</th>
<th>Inj. speed [mm/s]</th>
<th>Mold temp. [°C]</th>
<th>Cooling time (s)</th>
<th>Initial crack [shot no.]</th>
<th>Critical failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged 1</td>
<td>220</td>
<td>80</td>
<td>25</td>
<td>5</td>
<td>70</td>
<td>110</td>
</tr>
<tr>
<td>Unaged 2</td>
<td>220</td>
<td>40</td>
<td>25</td>
<td>5</td>
<td>95</td>
<td>143</td>
</tr>
<tr>
<td>Aged 1</td>
<td>220</td>
<td>40</td>
<td>25</td>
<td>5</td>
<td>50</td>
<td>110</td>
</tr>
<tr>
<td>Aged 2</td>
<td>220</td>
<td>40</td>
<td>25</td>
<td>5</td>
<td>30</td>
<td>85</td>
</tr>
<tr>
<td>Aged 3</td>
<td>220</td>
<td>40</td>
<td>25</td>
<td>5</td>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td>Aged 4</td>
<td>220</td>
<td>40</td>
<td>25</td>
<td>5</td>
<td>12</td>
<td>45</td>
</tr>
</tbody>
</table>
Fig. 6. Crack propagation in different IM shots (a) unaged mold insert (b) aged mold insert (c) after 75 shots (d) and (e) after 100 and 75 shots respectively and (f) the heart feature part deformation.
Fig. 7. (a) Crack locations on the unaged mold inserts (b) Unaged mold inserts after 120 shots (c) aged mold inserts after 105 (d) mold inserts failure after 110 shots (e) and (f) aged mold inserts after 35 and 45 shots.

As discussed in [1] there is a heat transfer from the hot melt material to the tool, thus the mold inserts in IM process experiences cyclic thermal variations. Although cooling channel in the mold provides faster cooling time and increased production, uneven thermal changes lead to stress. These cyclic thermal variations may cause a thermal fatigue in the mold, which generates crack and final fracture. Thermal fatigue may occur without mechanical loads, but in IM process, mold inserts are subjected to both temperature changes and varying pressure loads. The cyclic heating and cooling conditions have crucial roles in failure mode, and the thermally-induced stress occurring in the mold can be calculated by:

\[
\sigma = \alpha E (T - T_{ref}) = \alpha E \Delta T
\]

where \( \alpha \) is the thermal expansion coefficient, \( E \) denotes the modulus of elasticity and \( \Delta T \) is the temperature change. It should be noted that thermal fatigue is related to the thermal conductivity and changing this parameter leads to different thermal strength of the component. Although fast cooling can be achieved by a large temperature difference(\( \Delta T \)), regarding to Eq. (3) it increase the thermal stress. In fact, fast cooling is a large temperature difference, which is \( \Delta T \) in Eq. (3). Therefore, an increase in \( \Delta T \) increases the thermal stress. Moreover, according to Eq. (3) utilizing a material with low modulus of elasticity and low thermal expansion can decrease the thermal stresses. Therefore, these factors must be considered in manufacturing and in the context of the structural integrity of 3D printed mold inserts.

Apart from crack analysis on the mold inserts, surface roughness measurements were carried out in different locations on the inserts. The spots were located on the outer surface of the inserts and inside the hearts and bricks as shown in Fig. 8(a). For each location, the measurements were carried out three times in different spots for statistical consistency assurance. The roughness measurements were conducted using a 50x
magnification lens with exposure time of 1.7 ms. The average values of the surface roughness Sa (arithmetical mean height) is shown in Fig. 8(b). Nearly similar trends were observed in different areas on the aged and unaged mold inserts where higher roughness value recorded on the aged mold inserts. Surface morphologies in different mold inserts in Fig. 8(c)–(e) illustrates the changes on the surface of the unaged, aged before IM and aged after IM experiments respectively.

It should be noted that a difference between defect and imperfection should be highlighted. In fact, defects can lead to mechanical failure and rupture, while imperfections can detract some part of material but do not necessarily cause failure. With reference to the ASM handbook [33] imperfection is a deviation from ideality. By this definition voids (bubbles), discontinuities and surface blemishes should be considered as imperfections. Here, the fractographic analysis shows some voids in the studied mold inserts, which have no influence on the performance of the part and its strength. Since these voids are very small and placed in the section where strength is not critical for the mold inserts, we concluded that these voids are not effective in fracture of the studied mold inserts.

As it is illustrated in Fig. 8, surface roughness changes in the aged mold inserts. In fact, accelerated thermal ageing somehow changes failure types, which lead to different surface roughness. The failure transformation in the aged mold inserts before and after IM process was visible from the surface morphology therefore, in addition to the previous crack locations (sharp corners and thin walls) on the mold inserts, cracks occurred in further area such as at the corner of the mold inserts. Moreover, Fig. 9 shows injection molded parts (heart features) measurement for both unaged and aged inserts. In terms of the features height different size of the features observed based on the inserts life and propagated cracks all over the inserts, which were all smaller.
than the nominal geometry of the structures. Regarding the lower angle of the features (Fig. 9(b)), the ageing affect to enlarge the angle of the structures in all aged batches. The unaged IM parts demonstrated less variation in comparison to the aged IM parts, which shows the influence of the ageing on the replicated structures. A slightly different result for the left and right side of the insert was mainly due to the gate location and IM direction in filling the parts.

![Fig. 9. IM unaged and aged parts measurements (a) height and (b) angle of hearts features.](image)

Mechanical failures can be explained by performing microscopic investigations. To this aim, we conducted optical microscopy investigations, thus the cracks and surface roughness presented in the previous section were found. Observations under the microscope indicated that not only crack propagation velocity is increased in the aged specimens, but also, the numbers of cracks significantly increased in this group of the specimens. As number of cracks is increased in the aged specimens, induced residual stress from thermal ageing can be considered for the aged molds. This is a significant issue, since its deals the stress and environment which the mold may have been exposed to in its service life. In fact, failure in the case of polyethylene can be related to a decrease in the micro-ductility, which is important in the study of fracture, and is consequence of stress and environmental conditions [34].

![Fig. 10. Average of crack propagation rate over the number of specimens measured in unaged and aged molds. Each value represents the average of five specimens.](image)
Fracture of engineering components is an important issue, strongly dependent on the strength of components and working conditions. In this respect, crack propagation plays a central role as it can provide useful information for failure analysis. In the current study, we compared crack propagation rates of unaged and aged molds to show the effects of accelerated thermal ageing on real application of the mold inserts. Average of crack propagation rates in unaged and aged molds are illustrated in Fig. 10. The effect of ageing (temperature) on the crack growth rate can be clearly seen. These cracks propagation rates are obtained according to the recorded cracks via optical investigations during the mold usage. The cracks growth increment in each mold is investigated periodically after an interval of 8–10 molding cycles. This procedure was employed to determine the influence of thermal ageing on crack growth. As we expected, higher crack propagation rates is observed in the aged mold inserts compared to unaged mold inserts. It is observed that crack growth rate is different in unaged and aged molds. This phenomenon may be attributed to the rate dependent nature of the mold material.

The generated cracks in the studied molds have been considered as important contributors to stress concentration in the tested molds. In this study, the created cracks introduced stress concentration, which helps the maximum stress, exceeds the theoretical strength, and therefore subsequent fracture occurred. Cracking is apparently progressive and propagates intermittently, with increasing rate during a first period of production, and later stabilizing at a certain propagation speed (approximately 80–100 µm/shot from shot no. 83 in unaged inserts and 180–200 µm/shot from shot no. 63 in aged inserts). Although lifetime of the insert mold cannot be calculated directly from the obtained results, the presented findings indicated role of ageing in fracture behavior. The achieved results indicated that crack propagation rate is increased with increasing temperature at which the inserts have been exposed prior production. With exposure at higher temperature, less energy is required to propagate the existing cracks in the molds.

6. Conclusion

Due to the favorable and unique properties of additive manufacturing technologies, their applications have been significantly raised and utilized in various manufacturing process. Since mold design and fabrication are challenging issues in injection molding process, AM techniques are employed for the fabrication of mold inserts to tackle those challenges, particularly in the prototyping phase, for short to medium production runs, and highly customized products. In the current study, accelerated thermal ageing is applied to injection molding inserts produced by additive manufacturing DLP technology. As molds are subjected to the cyclic thermal variation during their service life, investigation on behavior of the molds under this condition is beneficial. Indeed, the response of the molds to the thermal conditions determines cyclic stresses was studied. Thermal ageing leads to crack formations making the most affected areas in the mold inserts. Thermal stress in the molds can be decreased by increasing cooling time, but it leads longer cycle time and decreased productivity. The cracks propagated much faster in the aged mold inserts and lower number of shots were reached (maximum and minimum number of cycles were 50 and 8 respectively) than in unaged inserts (that reached 95 cycles before initial cracks appeared). In terms of the cracks location, it was noticed that the cracks appeared in different regions of mold inserts with dissimilar failure. Moreover, the surface roughness analysis indicated higher roughness in the aged mold inserts in different location of the mold inserts.

Experimental usage of unaged and aged molds, and microscopic investigation on their surfaces, proved that thermal ageing speed up the fracture process. In the present work, experiments proved that generated cracks in the molds kept growing in unaged specimens as well. However, there is no clear mathematical relationship that could explain the specimen performance (i.e. strength) and exposure time. Although this investigation has only been applied to one mold inserts with the selected design with described specifications, this experimental practice could be extended to various mold insert designs with more complex geometries and different materials. The research has shown an influence of accelerated thermal ageing on the behavior of mold inserts mold fabricated by the AM technique. According to the achieved results, accelerated thermal aging by means
of exposure to the elevated temperature is suitable method for a fast identification of the 3D printed molds behavior. The investigations indicated a clear effect of ageing on crack propagation. In particular, the accelerated thermal ageing increased crack propagation rate in the tested molds.

The utilized mold inserts experienced thermo-mechanical loads, and the prediction of the lifetime of these mold inserts is of great importance to the industry. In this respect, the combination of thermal cycling and mechanical loading tests is a time and cost effective way to obtain crack propagation data, which can be used to predict thermal cracking processes. Although mold inserts experiences elevated temperature during their service life and have shorter lifetime than inserts produced by conventional tooling technologies, we conclude that AM technique for producing mold inserts is a promising alternative to reduce new product development of molded components. However, in order to accelerate adaptation of AM components various advances are required. For instance, profound knowledge on the mechanical behavior of these parts and predictive modeling of behavior of AM parts during manufacturing process and in their service life are necessary.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Appendix A. Supplementary material**

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**References**


