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Research Paper

Categorization of Failures in Polymer Rapid Tools Used for Injection Moulding

Anurag Bagalkot[1], Dirk Pons [2] *and Digby Symons[3] and Don Clucas[4]

[1] University of Canterbury; anurag.bagalkot@pg.canterbury.ac.nz
[2] University of Canterbury; dirk.pons@canterbury.ac.nz
[3] University of Canterbury; digby.symons@canterbury.ac.nz
[4] University of Canterbury; don.clucas@canterbury.ac.nz
* Correspondence: dirk.pons@canterbury.ac.nz; Tel.: +64-33-695-826

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Abstract: Background- Polymer Rapid Tooling (PRT) inserts for Injection Moulding (IM) are a cost-effective method for prototyping and low volume manufacturing. However, PRT inserts lack the robustness of steel inserts, leading to progressive deterioration and failure. This causes quality issues and reduced part numbers. **Approach-** Case studies were performed on PRT inserts and different failures were observed over the life of the tool. Parts moulded from the tool were examined to further understand the failures, and root causes were identified. **Findings-** Critical parameters affecting the tool life and the effect of these parameters on different areas of tool are identified. A categorization of the different failure modes and the underlying mechanisms is presented. The main failure modes are: Surface Deterioration; Surface Scalding; Avulsion; Shear Failure; Bending Failure and Edge Failure. The failure modes influence each other and may be connected in cascade sequences. **Originality-** The original contributions of this work are the identification of failure modes and the relationship with root causes. Suggestions are given for prolonging tool life, via design practices and moulding parameters.

Keywords: Rapid Tooling; Additive Manufacturing; Failure Modes; Injection Moulding

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1. Introduction

1.2 Background

New Product Development (NPD) is a key success factor for growing organizations as they are constantly re-engineering and developing new products to stay competitive [1,2]. Transitioning of new products from research and development (R&D) stage to prototyping stage and finally the manufacturing stage is a common problem for organizations of all sizes [3]. The stages of NPD from an engineering perspective are shown in Figure 1.

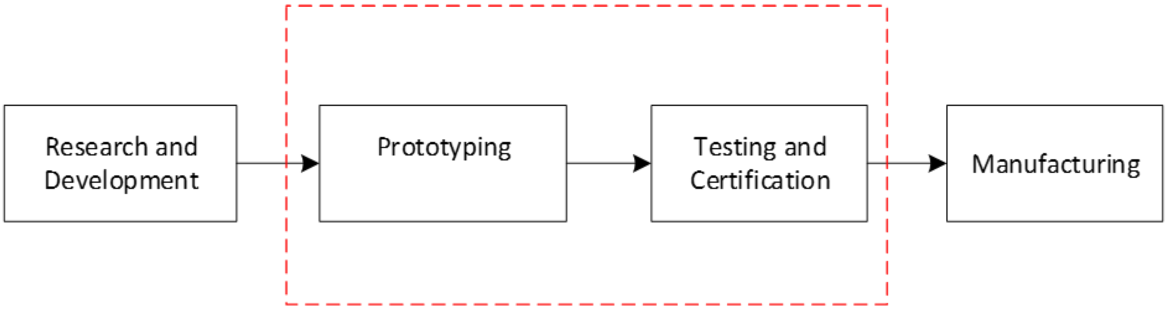

Figure 1: Stages of an NPD process from an engineering perspective.

The middle phase of the NPD process highlighted in Figure 1 is often the difficult phase due to cost and time constraints; especially for innovative start-up firms and small organizations [4]. In the case of polymer products, Injection Moulding (IM) is one of the most widely used polymer processing techniques. Conventionally IM tools are machined out of blocks of steel, aluminium or copper-beryllium alloys, the choice of mould material is dependent on factors such as moulding material, complexity of part, required life and the available budget [5-7]. In cases of low volume production, the capital cost of injection moulds is the largest cost component of an injection moulded part followed by the moulding material and processing costs [8]. Complex product geometry requires complex tooling which increases the cost and lead times if manufactured by conventional methods, which does not work well for keeping the costs of prototype tooling low [6,9]. Hence, the NPD process for injection moulded parts typically faces issues (delays) during the prototyping and testing phases. Since more than 35% by weight of all polymers is by IM the highest demand for low cost tooling is from the IM industry [8]. To stay competitive industries are looking to reduce wastage of raw materials, shorten product lead times and eliminate the need for expensive tooling [10]. In the above situations industries increasingly turn to Additive Manufacturing (AM) to solve these challenges via direct part production [11]. However, there are disadvantages: lack of material availability; varied material properties; inaccurate representations of the final part; poor surface finish. For accurate evaluations of a prototype industries prefer to manufacture prototypes using the same material and same process as the final part. In such situations industries may use Rapid Tooling (RT).

1.2 Polymer Rapid Tooling (PRT)

RT is a process that uses AM techniques to build tools at low cost. RT negates the need for complex conventional machining operations and direct labor and instead uses an additive approach of building objects layer by layer [12,13]. The initial push for developing objects quickly without the need for complex tooling came from the American automotive industry [14]. RT involves both the use of polymer and metal AM systems. However, the cost of metal AM systems and operating consumables are significantly higher than polymer-based AM systems. Rapid Tools built using polymer AM systems are referred to as Polymer Rapid Tooling (PRT). Fluid based AM processes such as SLA and MJ are the most commonly used processes to manufacture PRT inserts for injection moulding. Selective Laser sintering (SLS) and Fused Deposition Modelling (FDM) have also been used but not as commonly as the fluid-based AM processes [15].

1.3 Failure of Polymer Rapid Tools

This section deals with the various types of failures and its causes presented in the literature. Most of failures were classified as mechanical failures that occurred due to high injection pressure and higher melt temperature. The second most common reason of failure was due to insufficient draft on the walls of the tool. Several suggestion have also been identified by authors to improve tool life and avoid failure.

1.3.1 Failures Due to Mould and Melt Temperature

The first PRT inserts made using SLA technology were not robust and failed during the start-up of injection moulding process, they had a very low thermal conductivity which caused thermal degradation and resulted in mechanical failure [16]. The life of a PRT insert is largely dependent on the resin being moulded and the moulding parameters in use [17]. The co-efficient of thermal expansion in polymers varies with the temperature, at temperatures above the glass transition temperature (T_g) of the material, the co-efficient of expansion increases significantly. This causes the mould to expand drastically and fail sometimes [18]. Adjusting the process parameters to keep the tool temperature below its glass transition temperature (T_g), to avoid softening of the tool, is one suggested solution to avoid such failure [19]. However, this solution is only possible if the moulding polymer allows a lower mould temperature, for polycarbonates requiring higher mould temperatures it is not applicable.

1.3.2 Failures Due to Injection Pressure

Failure typically occurs after several shots. Since the shear and bending forces induced by IM should not increase, it is therefore suggested that failure occurs due to a change in mechanical properties of the tool [16]. PRT inserts were seen to be deforming and failing catastrophically due to the pressure exerted by the molten polymer during the injection and packing stages of the moulding process [20]. Inserts tend to fail if the stresses created by the flowing polymer are more than the yield strength of the tool at that temperature [21]. The injection of polymer is also known to cause stresses on features which may lead to crack propagation and eventual failure of the insert [22]. Static friction between the polymer mould and part determine the ejection force, the static friction increases with increase in mould surface area. Cooling cycles can determine the amount of shrinkage and thereby the ejection forces as well, higher ejection forces will lead to tool wear and a gradual failure [17]. The surface roughness of moulds plays an important role in the ejection forces, small build-up layers and high gloss finished moulds experience smaller ejection forces [23]. There is also a possibility of surface smoothening over the life of moulds which can be good for tool life but can lead to excessive flashing. 3D printed tool designers recommend having draft angles of about 5% in polymer moulds for the ease of ejection of parts, higher draft angles will lead to easier part ejections [24].

1.4 Opportunities for Development

SLA based materials such as Accura Bluestone® from 3D systems [25] and Somos® Perform from DSM [26] are more suited to produce PRT inserts than the MJ materials such as Digital ABS and Visijet M3-X reported in this paper [27]. These materials contain reinforcement and have better thermal performance. However, the cost of AM machines that are required to print these materials is high and is generally not accessible to smaller industries. The journal literature for polymer-based RT is predominantly based on the SLA process and lacks data for other processes such as MJ and FDM.

The cost of AM machines and material used in the MJ process are significantly lower compared to the SLA process. Hence, there is still a place for RT tools printed via the MJ process. Especially for Start-ups and small organizations where keeping costs low is one of the biggest challenges. Currently there is ongoing work into the use of the MJ process to create low cost PRT inserts and methods for strengthening the PRT inserts. Application of a metal layers (coatings) on the PRT inserts has been suggested to improve properties such as wear resistance and hardness [28,29]. Compositing FDM parts with high strength resins filled into the voids printed has also been known to improve the strength of PRT inserts [30]. However, PRT inserts made from the MJ process tend to fail abruptly and have life issues. The life of these inserts is dependent on factors which are not very well documented. Understanding the failure modes, the possible causes of failure and developing a process to prolong the tool life can be quite beneficial to create low cost tooling.

Therefore, this paper focuses on categorization of failures that occur during the injection moulding process using PRT inserts manufactured by the Material Jetting technique.

1.3 Aim

PRT inserts lack the strength and robustness of conventional steel and aluminium inserts and typically only last for 50-100 shots before the surface starts deteriorating and features on the insert begin to fail. The materials for PRT inserts made from the MJ process are cross linked polymer systems (thermosets). These do not necessarily have a melting temperature, but instead have a glass transition temperature (T_g). Digital ABS® the most commonly used material for PRT, has a T_g of 53°C. The current industrial trend is to use PRT inserts to mould polymers with relatively low processing temperatures of about 150-200°C. These include commodity resins such as polypropylene (PP), acrylonitrile butadiene styrene (ABS) and polystyrene (PS). These resins have a good melt flow index and require mould temperatures in the range of 45-50°C which is below the T_g of Digital ABS®. Lexan-943-A® is a resin commonly used by the aerospace industry for cabin interiors. However, the mould temperature required for moulding Lexan-943-A is 80-95°C, which is higher than the T_g of Digital ABS®, and the processing temperature is in the range of 285-315°C. This presents a challenging opportunity to develop a process that would help in achieving low volume production (10-100 parts) of aerospace cabin interior parts (polymer) using PRT inserts.

The main aim of this study was to identify and categorize the different failures that occur in a PRT insert when used for injection moulding resins with processing temperatures above 275°C. We are particularly interested in analysing real-world components and determining best practices for users. Understanding of failure modes and the underlying mechanisms will help with predictions of tool failure and assist improvements in the operating life of PRT inserts.

2. Materials and Methods

We applied a case study methodology to real production parts. Three case studies were performed, of progressive complexity both in terms of moulding and part geometry. The first case study was a standard test specimen used for flame and toxicity testing in the aerospace industry, the geometry is flat and did not involve any complex features. The challenge in case study 1 was to completely fill the mould without damaging the PRT insert. The second case study was an electronic enclosure used in the navigation industry, the geometry was complex as it had features such as thin walls, bosses and ribs. The third case study was a finger guard used in the aerospace industry, the mould geometry did not have a flat parting line and had walls with no draft on them. The complexity in case study 3 was to avoid scalding of the tool due to lack of air vents. The details of case studies are shown in Table 1.

Case Study	Type of Part	Reason for Study
Case Study-1	Standard Flame Test Specimen	Feasibility Testing
Case Study-2	Electronic Enclosure	Understanding Failures
Case Study-3	Aircraft Interior Part	Improving Tool Life

Table 1: The type of part and reason for each of the case study.

In all case studies the moulding has been performed with an aerospace resin: Lexan 943-A. The key issues are that the mould temperature required for processing Lexan 943-A is higher than the T_g of the PRT material. Hence the mould is operating under conditions of extreme thermal overload.

The case studies were devised based on a progressive regime of improving the tool life of PRT inserts. The findings from how the failures occurred in case study-1 were used to inform the design of case study-2, etc. For example, case study-1 gave important insights into the need to control injection pressure to avoid failure at first shot, and case study-2 gave insights into cooling time. The PRT insert from case study 1 which had failed on the 5th shot was examined, the runner wall had sheared due to incoming melt pressure. For case study 2 we used a low injection pressure and built it up over each shot until the pressure was sufficient to fill the cavity. The mould surface and features were examined after each shot for any potential defects. If any defects such as chipping, erosion, cracks were observed, the parameters for that shot were highlighted. Shot size, melt temperature and mould temperature were all kept constant, the injection pressure was increased until it was sufficient to fill approximately 85% of the mould. Examinations were done on the failure regions to determine the type and cause of the failure.

The process for setting up each case study, and for extracting failure insights is shown in Figure 2.

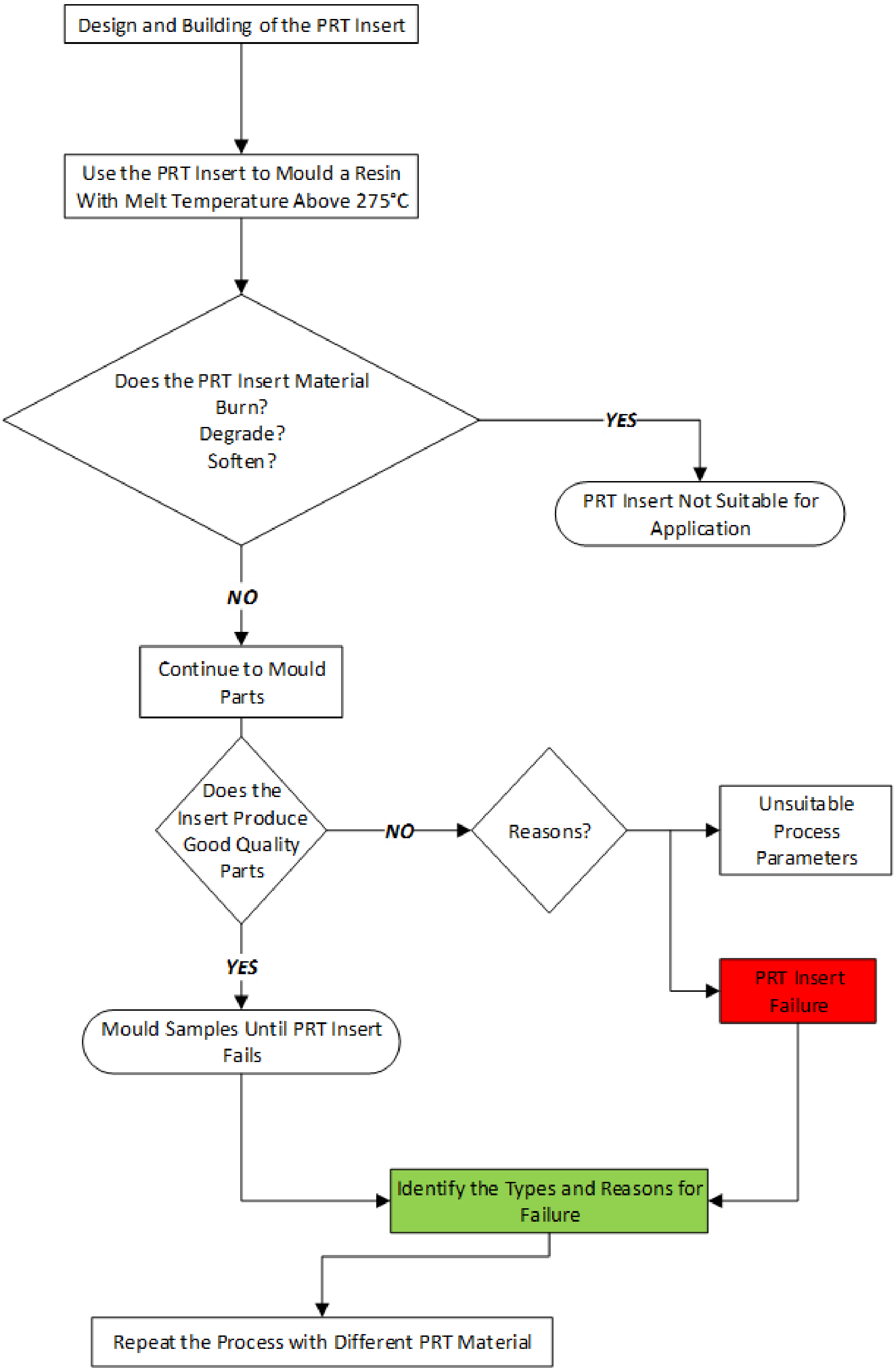

Figure 2: Process Workflow.

The different failures observed in the PRT inserts occurred at different times during the moulding cycle. We identify the shot number during which we first observed the signs of each failure type. Each part was inspected to detect failures, and likewise the tool. We continued the moulding process while the tool damage was minor (surface deterioration, surface scalding, bending), and terminated the test when catastrophic tool failure occurred.

2.1 Case Study Setups

2.1.1 Case Study 1- FAR Test Specimen

The flame and toxicity testing for aerospace parts are performed according to the standard tests specified in Federal Aviation Regulation (FAR) 25.853 and FAR 25.855. The FAR 25.853 requires the standard test specimen to be manufactured via the same process as the final part. The part chosen for this case study was a standard test specimen used for the vertical Bunsen burner test for cabin and cargo compartment materials. It is a flat rectangular plate (304.80×50.80×2.56 mm) and the solid model used for printing the core insert is shown in Figure 3.

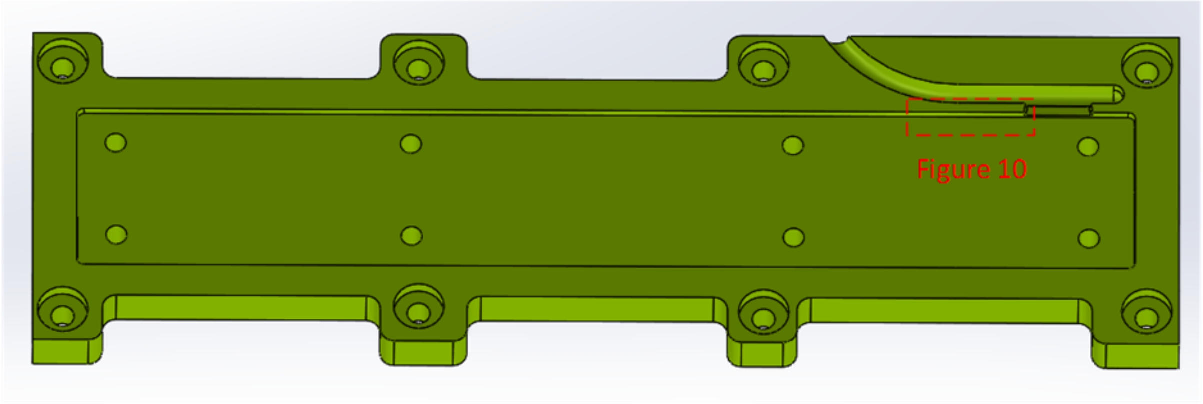

Figure 3: Solid model of the cavity insert used for printing

SOLIDWORKS 2016® was used to design the core and cavity inserts. The inserts were printed on a Stratasys OBJET 350 Connex 3 Polyjet Machine. Digital ABS® was the material used for printing the inserts with a 30-micron layer height setting and glossy print mode was used. The inserts were fitted into a standard master unit die (MUD) base, a 230-ton TOYO IM machine was used. No post processing was done other than water jet cleaning of the inserts to remove the wax support material. The process parameters used for injection moulding is shown in Table 2.

Parameter	**Value**
Resin Manufacturer	Sabic Innovative Plastics
Resin Name	Lexan 943-A
Resin Type	Polycarbonate/ Amorphous
Mould Temperature	80°C
Melt Temperature	310°C
Maximum Injection Pressure Set	180 MPa

Maximum Pressure Used	146.6 MPa
Fill Time	3.2 sec
Switchover Point	95% by volume
Highest Temperature of the melt	289°C
Cooling Time	55 seconds
Mould Open Time	Initially 20 seconds, was subsequently kept open until the mould temperature reduced to 80°C

Table 2: Process parameters recommended vs used for case study-1.

2.1.2 Case Study 2- Electronic Enclosure

Case study-2 represents a part with more complex geometric features including a boss, thin walls, and thin core pins, see Figure 4. An aerospace resin was injected: Lexan 943-A. The part chosen was already in production using a steel insert and was used as a reference. The inserts were printed on a Stratasys OBJET 350 Connex 3 Polyjet Machine. Digital ABS® was the material used for printing the inserts with a 30-micron layer height setting and the glossy print mode was used. The inserts were not hand polished as there was a risk of damaging the parting surface. A 450- ton injection moulding machine with a maximum injection pressure of 170 MPa was used. The mould temperature was set at 45°C to keep the tool below its T_g which is about 53°C. The recommended mould temperature from the resin supplier was 105°C. Table 2 compares the process parameters for meal moulds recommended by the resin supplier and the parameters used for the study.

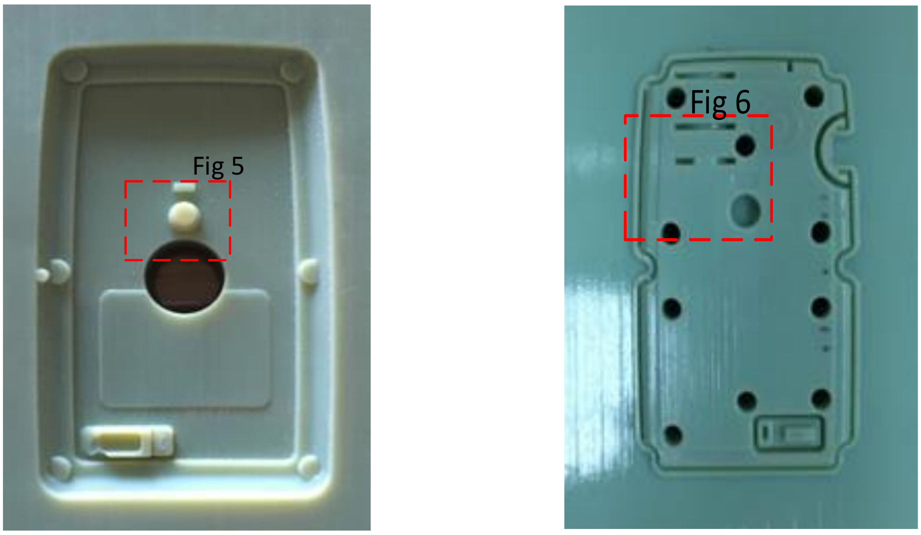

Figure 4: Core and Cavity Insert.

Parameter	**Recommended Value**	**Actual Value Used**
Resin Manufacturer	Sabic Innovative Plastics	Sabic Innovative Plastics
Resin Name	Lexan 943-A	Lexan 943-A
Resin Type	Polycarbonate/ Amorphous	Polycarbonate/ Amorphous
Mould Temperature	105°C	45°C
Melt Temperature	285°C	305°C
Maximum Injection Pressure Set	180 MPa	50 MPa
Maximum Pressure Used	N/A	41 MPa
Fill Time	0.87 seconds	0.55 seconds
Switchover Point	95% by volume	90% by volume
Highest Temperature of the melt	289°C	311°C
Cooling Time	15 Seconds	45 seconds
Mould Open Time	30 seconds	Mould kept open until mould reduced to target temperature of 45°C after every cycle

Table 3: Process parameters recommended vs used for case study-02.

2.1.3 Case Study 3- Aerospace Part

For case study-3 we used a production part for the aerospace industry, see Figure 5, which shows the core and cavity insert. The inserts were printed on a 3D systems ProJet MJP 3600 series printer. The material used was Visijet M3-X®, and an ultra-high definition (750×750 dpi) print mode with a 29µm layer thickness setting was used to print the inserts. For post processing the inserts were placed in an oven at 100°C for 1 hour; they were then cooled and scrubbed with a hot detergent to remove all the wax (support material).

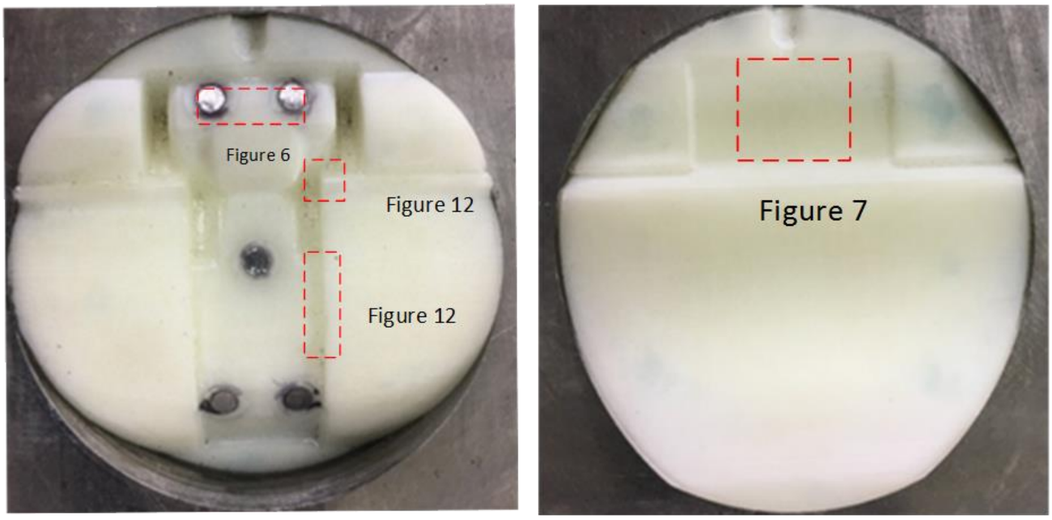

Figure 5: (a) Core insert for case study-3 fitted inside a master unit die. (b) Cavity insert for case study-3 fitted inside a master unit die. Tool outer diameter is 55mm.

A modified method of process parameter setting was used for the initial start-up process. Moldex3D flow simulation were used to determine the process parameters. The process parameters used for the study are shown in Table 4.

Parameter	Recommended Value	Actual Value Used
Resin Manufacturer	Sabic Innovative Plastics	Sabic Innovative Plastics
Resin Name	Lexan 943-A	Lexan 943-A
Resin Type	Polycarbonate/ Amorphous	Polycarbonate/ Amorphous
Mould Temperature	105^{o}C	45°C
Melt Temperature	285^{0}C	285°C
Maximum Pressure Set	180MPa	70MPa
Maximum Pressure Used	N/A	62MPa
Fill Time	0.5 seconds	1.2 seconds
Switchover Point	95%	90%
Highest Temperature of the melt	315°C	300°C
Cooling Time	10 Seconds	25 Seconds
Mould Open Time	5 seconds	Until the mould temperature after every shot reduced to 45°C.

Table 4: Process parameters recommended vs used for case study-3

1. Results

Various common failures have been identified during the 3 case studies. We have categorized the failures into three failure modes: Surface Failures (Crack Formation); Delamination (Crack Growth); Feature Failure (Fracture). The individual failure mechanisms are described below.

3.1. Surface Failures (Stage 1- Crack Formation)

3.1.1. Surface Deterioration/Micro Spallation

As the molten polymer enters the cavity it begins to cool while the PRT inserts begin to rise in temperature, at a certain stage of the moulding cycle the tool temperature is above the T_g of the tooling material which causes the tool to soften. During the injection stage as the polymer flows there is a constant shear between the molten polymer and the top surface of the tool resulting in erosion/spallation of the tool. The erosion tends to increase with polymers having a low melt flow index as they usually require a higher injection pressure. The erosion was microscopic and could not be seen by the naked eye on the inserts in-between shots, and the tool surface had failed completely at the end of production cycle. The surface erosion was detected only when the parts were viewed using a microscope. In Figure 6a, the brown protrusions are pieces of the tool material which have been eroded and stuck to the part, thus creating small voids over the tool surface. Since the tool surface is no longer flat the next moulded part will have protrusions similar to the eroded area. In Figure 6b similar protrusions are evident as in Figure 6a, but now are the same colour as the part. The surface degradation worsened after each shot. A magnified image of the deteriorated surface can be seen in Figure 6c, the magnified image shows both the protrusions moulded from the previous shot in white and the brown protrusions are new fragments of the eroded surface from the current shot.

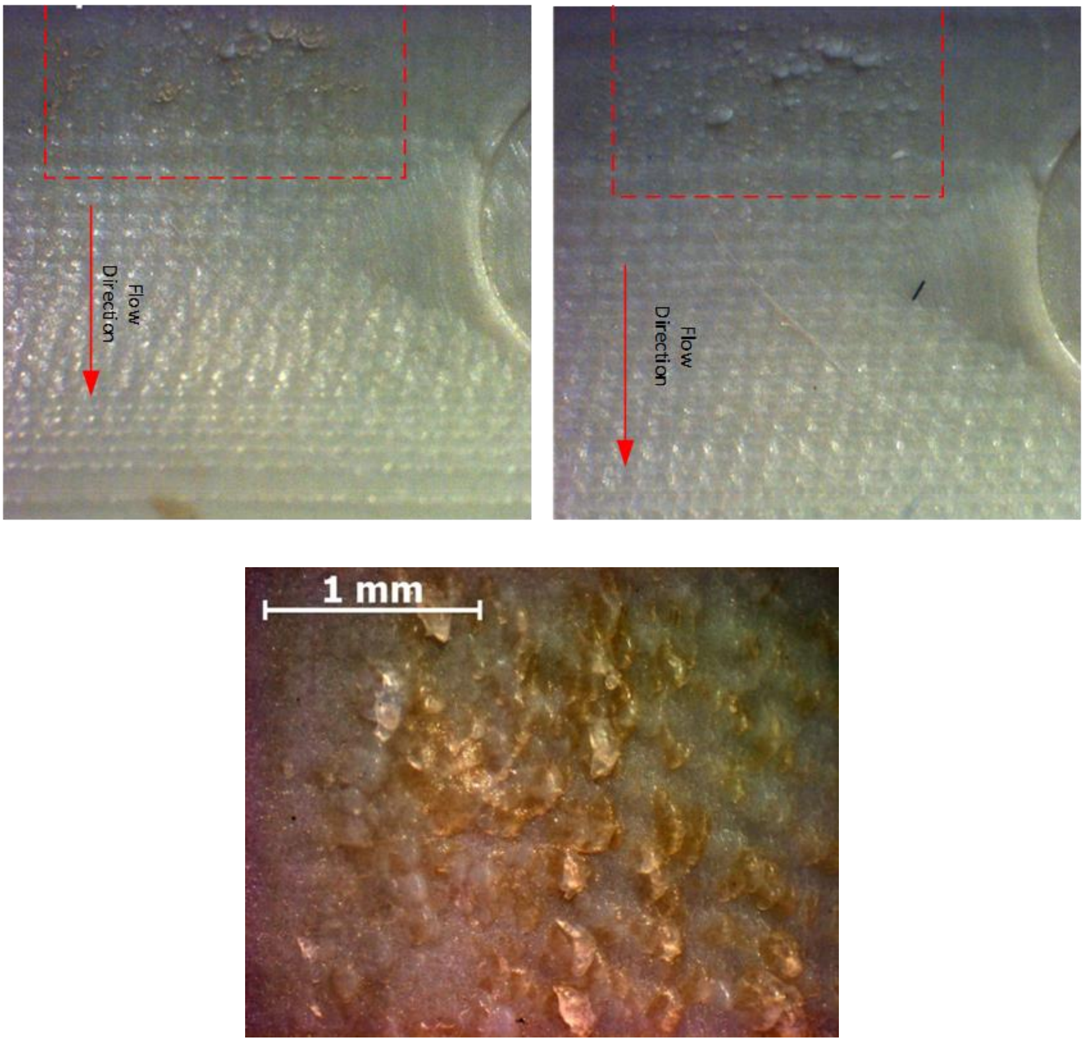

Figure 6: (a) Tool material eroded and deposited on the 7th shot from the tool. (b) Protrusions on the 8th part due to surface deterioration of tool in the same vicinity. (c) Magnified image of the area of eroded tool surface.

After each moulding cycle the parts were inspected for quality and once the part showed any signs of quality defect, we inspected the tool to assess tool damage. No quality defect was identified for the first 6 shots. A small area of deteriorated surface was seen on the 7th shot, on the tool and part. The surface deterioration worsened after each subsequent shot.

3.1.2 Surface Scalding

Surface scalding refers to burning of the tool surface due to the incoming polymer melt or the hot air/gases developed during the moulding process. This damage mode is characterised by browning of the tool in small patches, see Figure 7. Since MJ resins are thermosets they do not melt, at higher temperatures they usually degrade. Even though the tool temperature was kept below the *Tg* (53°C) of the tooling material before every shot, the tool temperature would rise as the molten polymer entered the tool. The first two case studies had a planar parting surface which made it easier for air vents to be printed, but for case study-3 the part had a curved parting surface and the faces were intersecting with the MUD base and hence no air vents were printed on the tool. Surface scalding was not seen in the first two case studies and was only seen in the third case and lack of air venting was suspected to be one of the reasons for the tool degradation. In addition, the periphery of the tool had discoloured and showed signs of scalding. This failure was evident at the 12th moulding shots. This rapidly progressed to catastrophic failure at the 13th as tool surface material was removed.

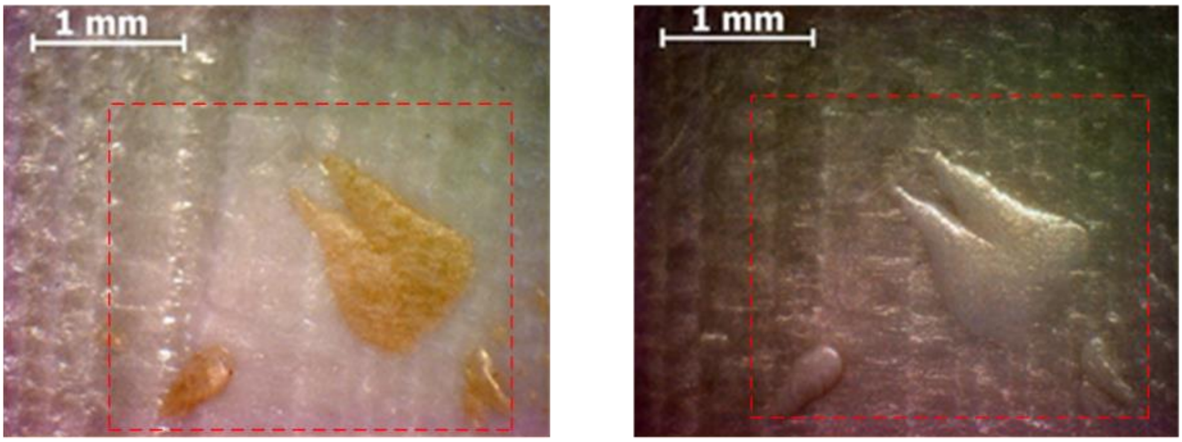

Figure 7: (a) Surface scalding patch attached to the part in shot 12 (b) Protrusion moulded in a similar area, shape and size because of the surface scalding, in shot 13. Scalded tool material has adhered to the part in (a), and hence the tool has lost material.

3.2 Avulsion/Delamination (Stage 2- Crack Growth)

Once the mould was 95% filled a second stage (hold) pressure was applied to force excess melt into the cavity to compensate for the shrinkage of the injected polymer. This second stage pressure resulted in adhesion between the deteriorated surface of the PRT insert and the part. Avulsion failure was observed in case study-2 on the core insert, see Figure 8 and Figure 9. The central hole on the core insert was initially observed to be deteriorating and as the cracks extended the part was seen avulsing chunks of material from the insert during each shot.

The insert at this stage was at a higher temperature than the T_g of the tool. We infer that this causes the tool to lose its strength and when the part is ejected, hence avulsion of the mould surface may occur. The term avulsion refers to ripping and peeling of the surface material of a body. Our proposed explanation is that during the first few shots surface damage occurs which leads to surface (micro spallation) and cracks. During subsequent shots, molten polymer enters these micro cracks and enlarges them; as the cracks grow more molten polymer is forced into the cracks before solidifying. During ejection this solidified polymer causes layers of the mould to be torn off. Avulsion failure is progressive rather than an abrupt failure mode.

Figure 8: Avulsion failure region on the PRT insert from case study-2. This failure mode is characterized by progressive peeling of the substrate material. The image shows the catastrophic end state of the process.

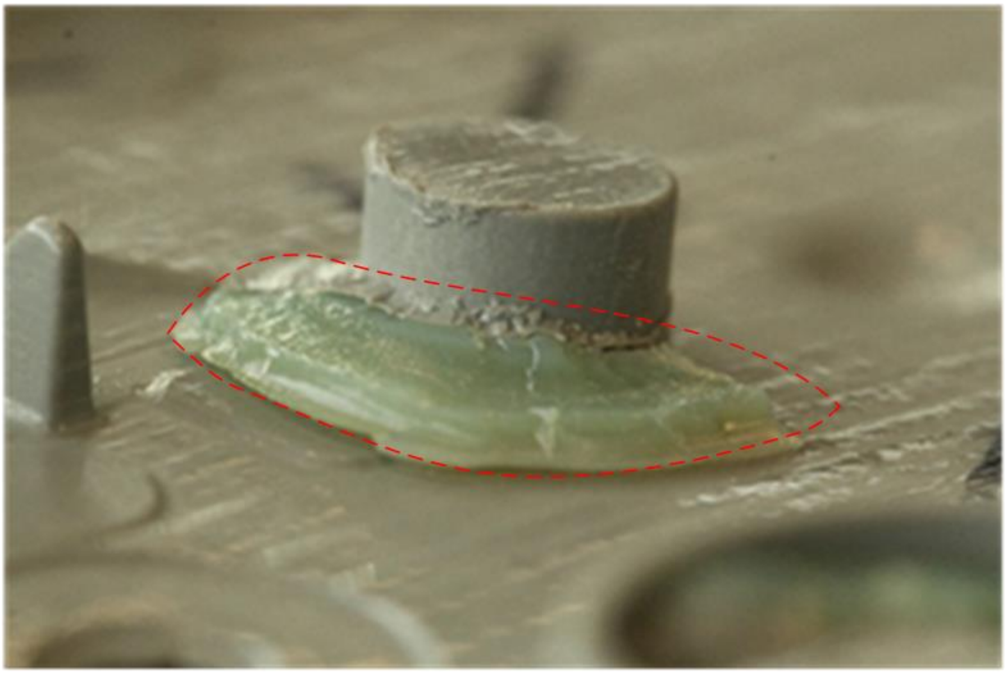

Figure 9: Moulded part showing peeled off tool material from the top surface. This occurred during the ejection of part. (Area highlighted is the tool material pulled out).

3.3 Feature Damage (Stage 3- Fracture of Features)

3.3.1 Shear Failure

During the injection stage the polymer melt is forced into the insert under pressure. The polymer melt while filling the cavity exerts a force on mould features such as walls, bosses, and ribs. This force is responsible for a stress which, if exceeds the ultimate tensile strength of the material at that temperature, may result in the failure of the feature. The injection pressure is highest during the start of the injection cycle and gradually reduces, this means features of the insert which are closest to the injection point (gate) are more susceptible to failure. Shear failure was observed during case study-1 on the runner wall of the PRT insert, see Figure 10. The high melt pressure during the initial process parameter setup phase caused the wall to shear and caused a catastrophic failure of the mould. The wall of the runner sheared off on the first shot but did not completely break off from the mould surface; during the subsequent shots the wall broke off the mould surface. Figure 3 shows the wall of the runner which sheared off. This was classified as shear failure due to the low aspect ratio (height/thickness) of the wall. This was a critical failure as it was a runner wall and we could not produce any more parts from the insert – it would be unsafe to try. We infer that shear failure may be a particular risk in areas with low aspect ratio thin walls which are close to the gate (melt entrance).

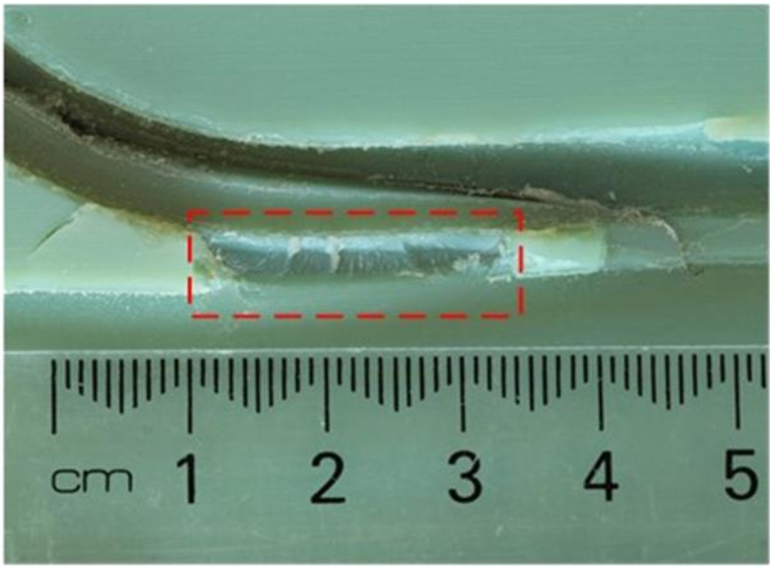

Figure 10: Shear Failure of the runner wall (boxed area) due to high injection pressure. See Figure 3 for location on the tool.

3.3.2 Bending Failure

A bending failure was observed in case-2, see Figure 11. This feature on the tool was supposed to create a hole on the part, but the boss feature was broken off the tool after 5 shots and all the parts moulded after it had a thick section instead of a hole. Although this made the part functionally defective, it was not considered a critical failure as it was still safe to operate the tool. The melt pressure was causing the boss to bend during the initial filling stage. This eventually led to a crack at the bottom surface and the failure of the boss in subsequent shots. The boss was situated directly 5mm in front of the injection point, this meant the boss was experiencing the highest pressure of all features on the tool.

The incoming polymer melt during the injection stage exerts a pressure on the front face of a feature leading to a deflection; as the melt front reaches the back face of the feature there is a reduced pressure difference between back and front face, and the deflection of the feature reduces. This cycle is repeated during each moulding cycle and may be responsible for the development of a crack which may eventually lead to complete failure of the PRT insert. Features with high aspect ratios (height/thickness) should in principle be the most vulnerable to bending failure.

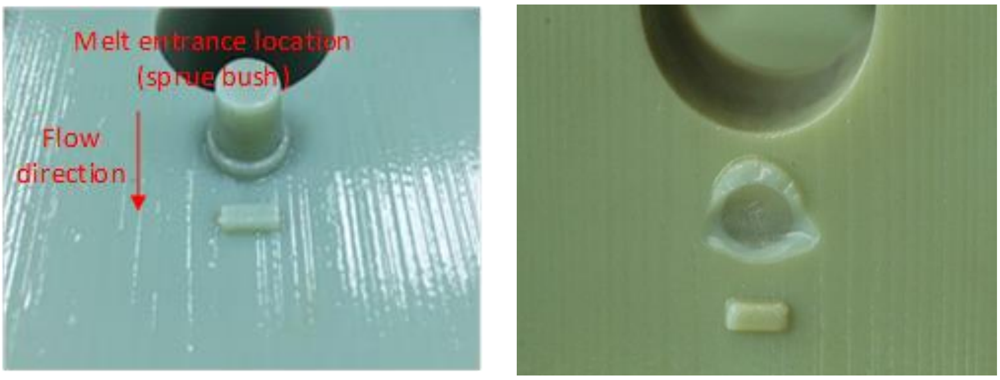

Figure 11: (a) Boss feature before moulding. (b) Bending failure of the boss feature due to high injection pressure. See Figure 4 for location on the tool.

3.3.3 Edge Fractures

The edges of the PRT insert deteriorated with each shot and small chips of the material were seen to be eroding from the edges, see Figure 12. This was particularly worse near the areas of the runner (melt entrance) where the melt pressure was high; the edge deterioration was less on the edges at the end of melt flow.

The other reason for the edge failure is the draft on the walls. During ejection there is constant friction between the part and the mould walls. The mould during the ejection stage is above its T_g and has low yield strength. The part while ejecting starts to degrade the surface (erosion) during the early shots and results in chipping when there is significant deterioration. An advanced version of the edge failure was observed in case study-3. During case study-1 edge failure was not a considered a significant failure because it did not pose any safety issues and was not flashing. However, the PRT insert in case study-2 was only used for 5 shots after which it failed via the shear failure mode. In case study-3 the tool survived the initial process parameter setup phase and the edges deteriorated progressively from the 9th to the 13th shot. During the ejection of the 14th shot a large shard of material was pulled out. After this shot the tool was flashing due to failure of the edge which was on the parting line of the tool. Surface erosion was seen on all the edges along the flow path and chipping was only seen on edges which had no draft. At the end of the 19th shot the fracture was about 5mm wide, and this was the final failure on the tool.

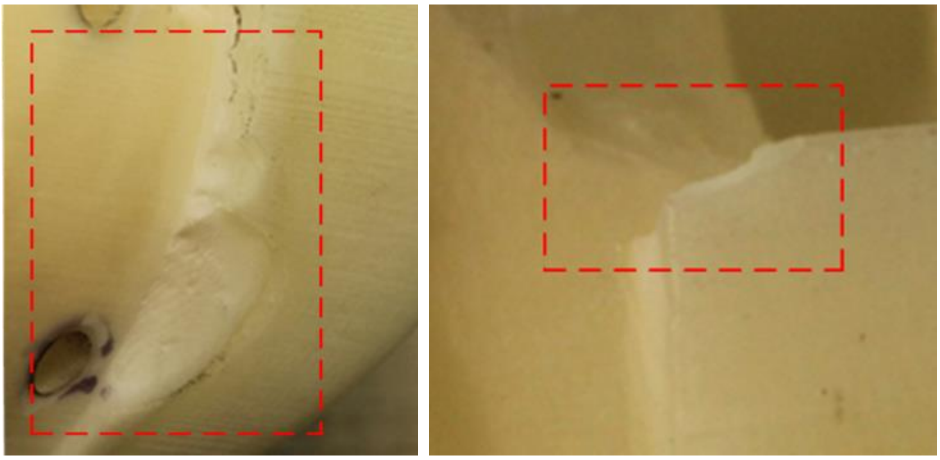

Figure 12: Chipped edge of the tool caused during the ejection of part. (b) Chipped corner of the tool due to injection pressure. See Figure 5 for location on the tool.

3.4 Categorization of Failure

Based on the above case studies, and after examining the moulds and sectioning the inserts in the cracked region, we identified a list of common failure modes. The main categories of failure were identified as: Shear Failure; Bending Failure; Avulsion; Surface Deterioration; Edge Failure; and Surface Scalding. Table 5 summarizes the types of failure, the probable reasons and the common regions of occurrence for each type of failure. This table may be useful as a guide for part, tool and process design.

	Failure Modes		**Type of Failure**	**Observed Regions**	**Possible Root Causes**	**Shot Number during which failure was first detected**
1	**Surface Failure** **(Crack Formation)**	1.1	Surface Deterioration	All over the surface, higher at the melt entrance	Low melt temperature, high mould temperature	7
		1.2	Surface Scalding	Regions around the gate and periphery of the tool	Shear heating, high tool temperature, lack of air venting	13
2	**Avulsion** **(Crack Growth)**	2	Avulsion	Directly in front of the gate and close to features	Ejection force, long cooling cycle, Draft angle	14
3	**Feature Failure** **(Fracture)**	3.1	Shear Failure	Thin walls and raised features (low aspect ratio)	High injection pressure, high tool temperature, Gate location	3
		3.2	Bending Failure	Raised features, high aspect ratio	High Injection pressure, High Tool Temperature, Gate location	5
		3.3	Edge Failure	Edges closer to the gate	Low draft angle, stress concentration, Gate location	13

Table 5: Categorization of Failures.

4. Discussion

4.1 Towards a Theory of Failure

We propose that multiple failure mechanisms are operating: thermal degradation of the surface of the tool material (scalding); crack growth due to creep (surface deterioration); localized tensile failure of surface (avulsion); crack formation due to applied stresses on tool features (bending and shear); crack growth due to intrusion of pressurized molten material with subsequent avulsion of tool material. The failure modes appear to influence each other and be connected in cascade sequences.

Injection pressure, injection temperature and mould Temperature are identified as major factors that contribute to the failure mechanisms. The combined effect is a progressive failure that leads to catastrophic failure after a few moulding cycles.

Three phases in the failure process

The results have identified the types of location where the failures initiate, and the appearance of the final failure. Generally, the progression shows three stages: crack initiation, crack growth and structural failure.

First stage: Occurrence of surface damage (surface deterioration, scalding), which then results in a crack. The surface damage occurs due to the tool temperature, melt temperature, and shear heating. The latter is affected by the injection pressure.

Second stage: Crack growth (avulsion). Once a crack forms its growth is rapid. A large extension of the crack was evident at each shot. In conventional applications of creep-fatigue the crack is hidden inside the bulk of the material. However, in the case of IM, there is an additional mechanism that is highly deleterious. This is the combination of intrusion of melt material into the crack, the solidification of that material, and the subsequent violent avulsion thereof at ejection. The ejection occurs at the opening of the tool and is driven by ejector pins. Hence there is another source of external loading on the features, other than injection pressure, that occurs at the end of each cycle. This process causes extensive damage to the cracked region, and this sets up the geometry for further damage at the next cycle.

Third Stage: Rapid destruction of the features within the tool, and a catastrophic deterioration of the integrity of the features and sometimes of the tool (shear and bending failure). This process is similar to the generally accepted creep-fatigue failure process but is accelerated by the intrusion effect. We propose the following conceptual map of the failure process, see Figure 13.

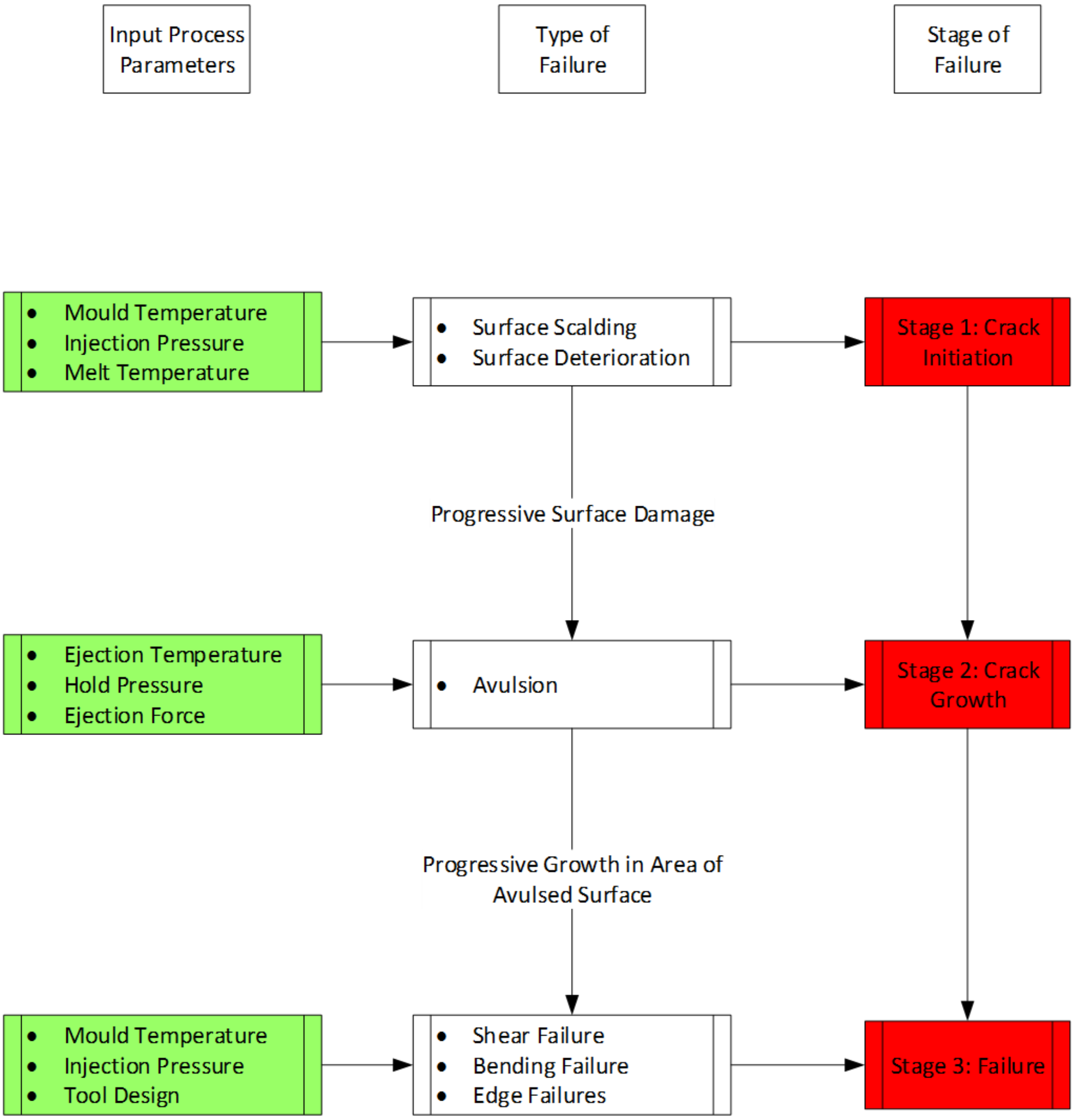

Figure 13: A conceptual map of the interaction between root causes and the failure modes.

4.2 Implications for Practitioners

The main implication for tool designers is to avoid gating (melt entrance) near to thin walls and raised features. This is because the injection pressure near the gate is the highest and can cause shear and bending failure of these features. Tool designers could consider using flow simulation software to evaluate the pressure consequences of different gating locations. They could also identify the problematic areas so that moulding technicians can monitor these locations after each shot.

Suggested Guidelines to Prolong Tool Life

The case studies have identified the stages of injection moulding and the tool locations where failure occurred. Based on this, guidelines for design and process-setting are proposed:

Tool Design Guidelines

1. Add thickness to walls nearer to the gate to give them extra strength. The current industry practice is to reduce the amount of printed material as it is expensive, but this practice leaves the tool vulnerable and may not serve the end purpose of cost reduction.
2. Avoid choosing gate locations close to features with high aspect ratios, as otherwise these could be vulnerable to early failure. The effect of injection pressure on features is high at the start of the filling phase and is much reduced at the end of flow.
3. Add flow leaders in the tool to help with flow in regions rather than increasing the pressure during moulding.
4. Design tools to have sufficient air venting. Air venting reduces the chances of surface scalding.
5. Avoid designing ribs and features that are perpendicular to the flow path, to reduce the area of contact between polymer melt and feature.

Process Setting Guidelines

1. The conventional method (used for steel and aluminium tools) for process parameter setting begins with using the highest injection pressure setting on the machine and optimising it on the subsequent shots. This may result in improper pressure setting and can lead to failure at start up as seen in case study 1. Instead, mould flow simulations could be used to determine the pressure required to fill the cavity. Consider starting moulding with 50% of that pressure and build up to the required pressure. This helps to avoid shear and bending failure at start up. (This is the first stage injection pressure. Hold pressure should be 50% of the injection pressure at start and then optimized too.)
2. Always maintain the tool temperature below the Tg of the tooling material always, use air jet cooling or increase mould open time between cycles. The yield strength of the tool reduces as the temperature increases. The effect is pronounced around the Tg of the material. The mould does not cool uniformly, and it is critical to check for hotspots on the tool and cool them before the next shot.
3. Use mould release sprays after each shot to help with ejection. Mould release reduces adhesion and may reduce the risk of avulsion.
4. A long part cooling time will result in the part shrinking and gripping onto mould surfaces causing problems during ejection. Cooling time should be kept as low as possible to avoid this. However, sometimes this will result in a part not being fully formed, in such cases increase the cooling in intervals of 5 secs.

4.3 Limitations of the Work

In this work we did not optimize gate location beforehand – instead the location was determined primarily from the usual perspective of design convenience rather than tool life. It is possible that a different gate location might have reduced some of the observed failures. In this study we used only the recommended settings from the machine manufacturers (3D Systems and Stratasys). We did not experiment with changing the settings for layer thickness, nozzle speed and infill density. It is possible that experimenting with different print settings and different post processing routes could alter the failure mechanisms. The failure analysis shown here is only relevant to 3D printed tools. Such tools are increasingly being used in industry, but generally for moulding benign materials (low melt temperatures) not the more demanding material shown here.

4.4 Implications for Future Research

The surface delamination (avulsion) is an interesting failure that starts below the surface of the PRT insert. Further research could be directed at better understanding this process, and how to avoid or suppress it for as long as possible. This is important because the inserts could still be safely used when small features were breaking off but became unusable only after avulsion occurred. Large scale avulsion quickly degenerates into catastrophic failure of the tool. Hence better understanding the causes seems to be an important future direction of research. The effect is anticipated to be material-specific.

A possible future line of enquiry could be to use a design of experiments (DoE) approach to determine which variables contribute most to the failure process, and how they relate. This is likely to be an expensive process given the destructive nature of the testing. In the current work we have used real parts, but this would be disfavored for a DoE approach. Instead it may be preferable to use small parts with representative features.

Print settings and post processing operations such as post curing, polishing and cleaning methods may also affect the failure processes and hence life of the PRT inserts. Hence a possible further line of enquiry could be to study the effect of these parameters.

Another possible research direction could be microscopic analysis of fracture surfaces. This might help identify the relative contributions of creep vs. fatigue vs. thermal degradation effects at the various stages of the failure. Our observations are that the white Visijet material is difficult to observe under optical microscopy due to poor contrast, but other colors or microscopy techniques may be more successful.

5. Conclusions

Case study investigations of PRT inserts used for IM suggest that the main failure modes are: Shear Failure; Bending Failure; Avulsion; Surface Deterioration; Edge Failure; and Surface Scalding. We have proposed a crack propagation theory and provide a conceptual map relating these failure modes to the root causes. The failure modes influence each other and may be connected in cascade sequences. Several suggestions are given for prolonging the tool life, via design practices and setting parameters. The latter includes the process of setting up the moulding parameters. The original contributions of this work are the identification of failure modes and the relationship with root causes and the proposed crack propagation theory.

This paper identifies the critical process parameters and their effects on different areas of the PRT insert. The conceptual map for failures presented indicates a gradual progressive failure of the PRT insert, from initial surface quality defects through to catastrophic feature failure. Mould temperature was a critical parameter since it affected all areas of the tool and contributed to multiple failure modes. Injection pressure was only significant in certain areas of the tool (injection pressure had little to no effect on failure of PRT inserts at the end of flow and had the highest effect on features closest to the start of flow path). Tool design was a factor in areas of the tool which had tall free-standing features.

The wider purpose of this work was to study the feasibility of: (a) Using PRT inserts to mould resins with melt temperatures above 250°C; (b) Determine the size of the parts that can be successfully moulded using PRT insert; (c) Determine the variety of features that can be safely moulded using a PRT insert; (d) Determine the number of parts that can be moulded before failure, and (e) the quality control of the moulded parts. In this study we were able to answer point (a): it is feasible to mould resins with high melting temperature of up-to 350°C, and we can expect about 14 parts from the mould before failure, for the cases under examination. Consequently it is possible to obtain a limited run of injection moulded parts from an inexpensive 3D printed tool. This is important, because the mechanical behavior of an injected molded part can be very different to a 3D printed part. Nonetheless further research is required to address the other variables (b) to (e), and increase the part count.

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