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Using Additive Manufacturing to Produce Injection Moulds Suitable for Short Series Production

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Abstract

Additive Manufacturing (AM) is claimed to be a serious competitor to traditional manufacturing methods in the production industry despite very few firms taking full advantage of its capabilities in bringing products to market. Many companies look towards AM as a direct manufacturing method, which is costly, time consuming and in industries such as children's toys, not in compliance with safety regulations. In recent times, plastics companies have looked towards using AM to manufacture moulds for injection moulding which can be used to produce end components. It is evident that firms have used such a process to produce low volumes of product, however there is no clear evidence to be found where these components are brought to market as a lone product or as a component of a product, nor is there any indication of the cycle life of a mould produced using AM. There are two potential market gaps for a process such as this to be implemented: manufacturing product during the New Product Development process in low volumes as a market tester, and producing customized products which can meet the demands of each individual customer at an affordable price. It was found that the most efficient way to develop this process was to first manufacture a Master Unit Dye (MUD), which held AM inserts which were moulds of the desired product. This MUD setup allowed for rapid changeovers in injection moulding machines along with adding the mechanical properties to this setup which were required for the injection moulding process. A sample product from a new product development team was used to prove the process was capable, producing up to eighty components using both SLA and Polyjet printed moulds without the moulds reaching their cycle life. The next step of this project is to select the most suitable products for this process from a new product development team and working with them to produce their product be using AM moulds with the intention of bringing these products to market. Products related to the toy industry

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manufactured using this method will be tested to determine whether they comply with EN-71 Toy Safety Standard to establish the benefits of this process over direct AM. Furthermore, a series of statistical analysis will be completed using process setups as variables to resolve which setup is best for the cycle life of each mould and the quality of the part it produces.

Keywords: Additive manufacturing; injection moulding; short series production; mass customization.

1. Introduction

The current manufacturing industry is unable to provide for the changing demand in consumer needs where mass customisation is becoming a growing priority. Mass customisation means to offer products or services which meet the unique demands of each individual customer, but which still can be produced with the economic efficacy which mass customisation offers [1]**.** Mass Customisation has seen some success in high margin products such as custom ships, it is however the average person where mass customisation remains largely unseen due to the inability to manufacture customised products efficiently [2] Where many believe that additive manufacturing is the solution to the question of mass customisation in low margin products, the outputs of such processes often times fail to meet the requirements of safety standards for certain product categories such as children's toys [3]. As mentioned, traditional manufacturing techniques such as injection moulding require too much capital investment per design for mass customisation to be economic. Additive Manufacturing companies have explored using their manufacturing processes to produce the tooling used in injection moulding with varied levels of success. Ultimately, these tooling designs have been used to produce low volumes of components and the cost of tooling remains significantly high as the physical volume of the tooling produced is quite large. This in turn means that the cost per component is still significant bringing the problem of mass customisation full circle [4].

A Master Unit Die is a setup used in injection moulding where a master die is adapted to receive, align, clamp and release insert dies of standard dimensions so that different designs of dies can be quickly changed in this master unit die, reducing the cost per die and the setup time associated with each product design [5]. It has primarily been used in mass production of components using metal moulds. There is scope to replace the metal inserts in a master unit die to inserts produced using additive manufacturing. The aim of this research is to select a sample product from an NPD student team module and to produce it using a combination of traditional manufacturing techniques and new age technologies to create a hybrid manufacturing process known as rapid tooling. A first iteration in design will see solely additive manufacturing used to produce moulds for a desktop injection moulding machine to prove the concept of rapid tooling. This will be built upon by using traditional techniques in toolmaking to produce a master unit die suitable for the apparatus available which will be combined with mould inserts produced using the new age technology of additive manufacturing. These pieces rapid tooling will be placed into injection moulding machines to manufacture the sample products chosen for this paper.

2. Background

Since 1986, additive manufacturing technologies have commutated the new product development process, particularly in the prototype phase, allowing designers to produce multiple iterations of 3D CAD models of their designs in quick succession without the need for human interaction. Rapid Prototyping works as a problem solving tool in new product development, allowing designers to check the functionality of their product before committing to the tooling investment required to produce the product in volume. Consequently, it is claimed that by using rapid prototyping techniques, the costs of new product development can be cut by up to 70% with time to market cut by up to 90% [6]. While rapid prototyping has done much to improve on the new product development process, many believe additive manufacturing technologies can be used to produce end products, especially in markets such as mass customisation markets with similar success as there has been with rapid prototyping. This has not come with ease however as the cost of each unit produced using additive manufacturing is typically higher than using a traditional manufacturing method, the lead time to produce a component can be higher than traditional methods depending on the complexity of the product and, depending on which Additive Manufacturing process is used and the purpose of the product being produced, additive manufacturing materials do not comply with many regulatory standards [7].

The most promising market for additive manufacturing to achieve in is that of the mass customisation market. As previously explained, mass customisation is to produce a product which meets the unique demands of the end customer for a similar cost to producing standardized high volume products. Additive manufacturing has the capabilities to produce unique products for a fraction of the cost when compared to traditional manufacturing means, however there are still lingering doubts to the metrology and materials properties of end products made using these technologies [8]. Traditional manufacturing processes such as injection moulding solve many of the issues highlighted above which additive manufacturing faces. However, traditional processes such as this are continuously refined so that they are capable of producing large volumes of product in as little time as possible with modern injection moulding machines capable of producing thousands of plastic components in a single shift. The tooling required for these components are often made from materials such as aluminum or tool steel which are expensive to machine and require often significant lead times. Therefore, for a firm to take any economic benefit from injection moulded components, they would need to be mass produced as to reduce the cost per component. However if mass customisation is to be implemented using existing manufacturing techniques, the cost of each individual piece of tooling for each unique design would result in uneconomic costs for the end user as well as significant lead times for them to receive their product [9].

Where much energy has been put towards developing each of these methods as individual processes for mass customisation, very little focus has been put towards exploiting the benefits of each process and combining them to create a unique process aimed at producing functional end products which have unique demands for the end user for an affordable cost. This paper proposes building on existing experimentation of using 3D printing in injection moulding and furthering this research to be able to produce end products suitable for consumer use. Free form fabrication processes have been used to create inserts to metal moulds which aid with the cooling process of traditional moulds showing the capabilities of additive manufacturing in full injection moulding machines [10]. Additionally, companies such as Formlabs have promoted the abilities of their printers to function using hand operated injection moulding machines [11]. To achieve a sustainable level of economic output for this manufacturing process a hybrid of additive manufacturing and traditional toolmaking must be used, taking the most beneficial aspects of both, to maintain a steady output of product while allowing tooling to be changed over quickly for the next product. Here lies the concept of a Master Unit Die, otherwise known as a MUD Box. A MUD Box is a metal framework which remains permanently fixed within an injection moulding machine but contains housings for mould designs which can be placed in and out of the setup in a matter of minutes. It is a one off piece of tooling manufactured using traditional CNC methods and traditional metal materials. It is composed of multiple sub-assemblies on a series of sliders which allow for the easy changeover of moulds and ejector setups. By using a MUD Box, it takes advantage of many of the benefits of steel tooling, such as strength, alignment and tool life while eliminating many of the repeatable costs associated with producing new tooling for every new product. It allows one to also implement inserts produced using additive manufacturing which result in lower costs per components of products manufactured while maintaining the needs of mass customisation. If implemented correctly, the benefits of this process could include an improvement on design for manufacture in the new product development process, the production of unique designs using traditional methods and the use of this process as a validation tool for metal moulds used in mass production. This in turn accommodates the maximum output of the injection moulding process with the minimum financial risk.

3. Design of Tooling

3.1. Design of Components.

Many of the traditional issues which present themselves with design for injection moulding in metal presented themselves in the design of plastic tooling, however the majority of these issues were amplified due to the poorer surface finish of a 3D printed mould when compared to an equivalent metal mould. Therefore, the moulds designed for the purpose of this paper were done so accordingly to compensate for the amplification of these issues. Two case study products were chosen from the two student NPD teams: A custom chess piece with a family crest embedded and a small c-clip used to hold ends of trousers which have been rolled up. Each of these products were put through a New Product Development (NPD) process which was taught during the associated module and each feature was selected based off of this process. These two products were chosen for injection moulding because of their simple single cavity design and their size which would allow for the initial exploratory testing of this process.

A typical product produced using metal moulds would have a draft angle between 1° and 3° to allow for the part to eject from the mould with ease. Because additive manufacturing uses a layer by layer process to build up solid 3D forms, small cavities between each layer allow for plastic to grip the face of the mould between each layer line, making part ejection more difficult. Therefore the draft angles of the components in this paper were increased to five degrees to allow the injected plastic to shrink away from the mould face with greater ease and eject without any issues [4]. Shrinkage of the product was assumed to be the same as it would be in a metal mould, therefore each cavity was scaled to 101% of the original size of the part. Runner systems and gates were increased slightly in diameter, this was to increase the flow rate of molten plastic, prevent flash freezing and reduce internal pressure on more fragile areas of the cavity produced. For the sprue of each component, a H13 steel insert was turned on a lathe and inserted into the printed blocks. This insert included a sprue which was electro sparked so it was tapered and a runner system. These inserts were manufactured to reduce the pressures on the printed plastic inserts caused by mechanical force and temperature of the screw of the injection moulding machine.

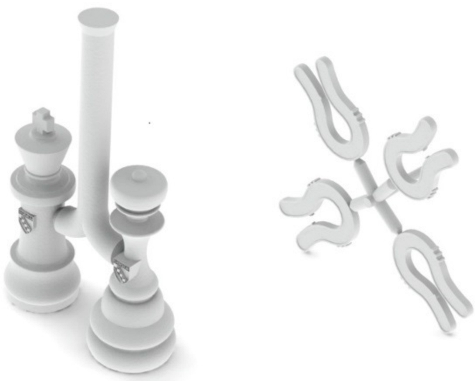

Fig. 1. Components were designed with injection moulding in mind with features such as draft and runner diameter increased to compensate for layer lines within the mould cavity.

3.2. Design of Master Unit Die

As previously stated a Master Unit Die is a metal framework which accommodates inserts of dies for injection moulding. Inserts are produced using additive manufacturing for the purpose of this experiment. The machine in which this Master Unit Die was mounted to was a Fanuc Roboshot S-2000i5A, a machine with a maximum clamping force of 4.9KN, which is relatively modest in the world of injection moulding. Therefore a decision was made to manufacture the Master Unit Die from aluminum. However, if this design was to be mounted to a larger machine, careful consideration would need be taken in selecting stronger metals for the manufacture of this assembly. This assembly was designed centrally around the point of injection on the machine. The fixed side assembly was constructed of three pieces mounted to the machine as one assembly. A retaining band held to the assembly with two short bolts held the insert in place and allowed for quick changeovers of inserts. The moving side assembly was made up of three sub-assemblies, a mounting plate, an ejector plate and a plate which holds the insert. When mounted to the machine, the moving side assembly was designed in such a way that the ejector plate and insert holder could be removed independently of the mounting plate. This accommodated the quick changeover of mould inserts and ejector setups, further enabling the prospect of rapid changeovers. The ejector plate was also able to slide forwards and backwards within the assembly and would be mounted to the ejector plate of the moving side platen so that the existing ejector system within the machine could be used.

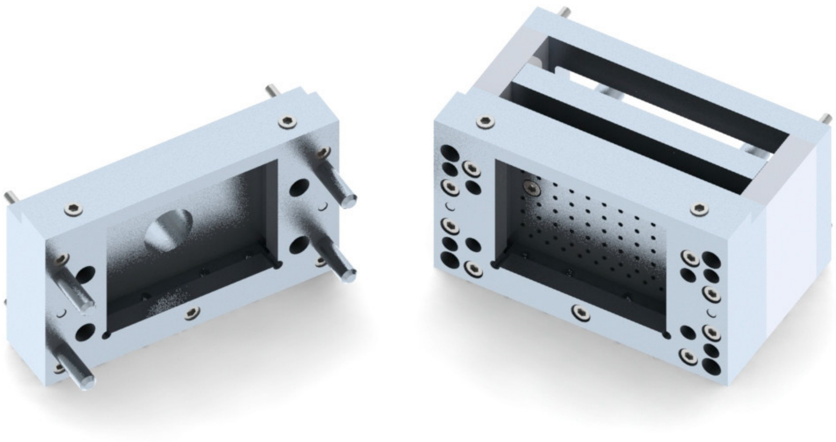

Fig. 2. A Master Unit Die will allow for quick changeovers of 3D Printed Moulds and overall reduce the cost and lead time of mould manufacturing

4. Printing of Tooling

There are multiple processes which can be used when producing components using additive manufacturing. Each process has its own unique set of advantages and disadvantages. Fused Deposition Modelling is the most accessible form of printing, however its low heat deflection temperature means it will fail immediately if used in an injection moulding process. Stereolithography and Selective Laser Sintering perform much better under such temperatures and mechanical pressures with SLA posing a superior surface finish. SLA was also far more accessible in this setting therefore it was decided to proceed with testing using this method.

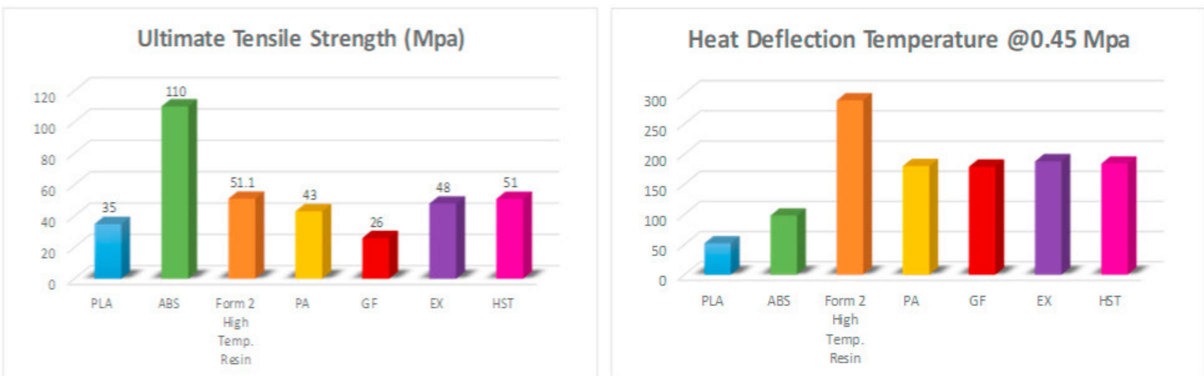

Fig. 3. (a) Ultimate Tensile Strength of considered materials (b) Heat Deflection Temperature @0.45 Mpa of considered materials.

The printer chosen to produce the mould inserts was a Formlabs Form 2. This printer was chosen for its ability to print in high temperature resin which too was developed by Formlabs and for its superior surface finish. Each print was orientated vertically on the print bed to reduce the need for support material, which can degrade the parting line and surface finish of the cavity when removed.

After the first print produced was noticeably warped, the orientation of the print was changed to ensure that the longest face of the mould ran parallel to the front of the printer. This was done to counter the linear movement of the printer, which would move from left to right to ensure the part was not sticking to the bottom of the vat of resin between each layer. This orientation was chosen as the second moment of area of this orientation was far greater than that of when the mould is rotated 90° through the z-axis, as it was during the first print which was warped. The part was printed with a layer thickness of 100µm, this could be reduced to 25µm but the additional time it took did not make up for the improvement in surface finish of the component. Each component printed using high temperature resin was cured at 60°C for 30 minutes under a 400nm UV light as per the recommendation of Formlabs. It was found that despite the best efforts of changing orientation and cure settings, each mould printed would have a slight warp. This never proved to cause failure in the moulds but some manual filing was necessary each time to ensure the moving and fixed side mould aligned square, which takes away from the rapid changeover concept.

5. Testing of Tooling

5.1. Chess Piece

Two iterations of the mould for the chess piece were mounted to a CR Clarke 25 Injection Moulding Machine, a hand operated desktop machine suitable to prove the concept of 3D printed injection moulds. The moving sides and fixed sides were each held in place using two 5mm bolts on either sides of the moulds. The ram was then aligned directly above the parting line of the moulds when clamped and placed in the retract position. The chamber was then heated to 180°C. Small pellets of polystyrene were loaded into the chamber and allowed to sit there for ten minutes until the plastic became molten. The moulds were shut and the ram was lowered using the hand crank. As the ram lowered it squeezed the plastic through the nozzle and in to the top of the moulds. Once the cavity was filled the moulds were let cool for sixty seconds, allowing the material inside to harden, before opening it to remove the parts.

5.2. Clip

The fixed side of the Master Unit die was placed first on to the fixed side platen. The five retaining bolts were tightened to finger tight. The moving side mould was then attached to the moving side platen and the retaining bolts were again closed to finger tight. The moulds were shut together ensuring the alignment pins and parting line faces sat square to one another. It was only then that the retaining bolts could be tightened fully. The ejector system for the given design was then set up on the machine before the moulds were finally inserted and held in place using the retaining bands. The procedure used to test for the clip adopted a “will it work” approach as there were no guidelines on how to operate such a setup. A small shot size was selected at first and one cycle of the operation of clamp, load, inject, pack, release and eject was ran to determine how far the first shot was from filling the cavity entirely. This shot size and packing pressure was gradually increased over multiple cycles until the cavity was filled accordingly and there was no flash caused by overfilling the mould. This approach was adopted due to how fragile the plastic mould can be. If one was to overfill the shot on the first cycle, it could cause the mould insert to fracture or de-laminate, wasting the time and capital of a would-be investor in the process. This mould was then run through several more cycles until a noticeable failure began to emerge.

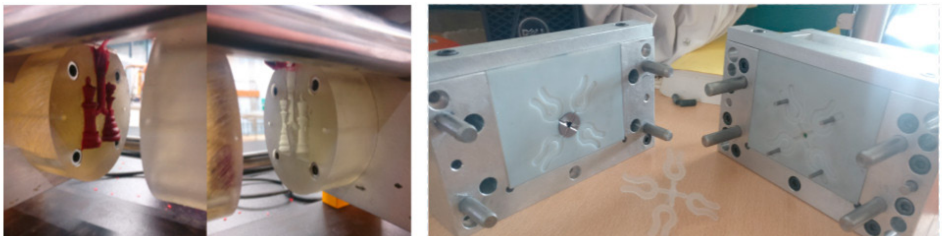

Fig. 4. (a) Setup of Revision 2 of the Chess Piece experiment. (b) Assembly of the MUD box with inserts and component produced.

6. Results

6.1. Chess Piece

Neither iteration of the tooling for the chess pieces proved to be a resounding success. Revision 1 was capable of producing two sets of components before the point at which they were mounted to the machine failed and the mould ultimately became unusable. The products produced had significant flash around the parting line of the moulds. Additionally, there was significant difficulty in ejecting the components as there was no real ejection system in place for this machine. Revision 2 of the mould proved more successful in solving the issues raised in Revision 1 but less successful in the number of components produced. The mould remained securely mounted to the machine and there was no flash in the first shot produced, however a persistence in ejection errors meant that the component remained securely stuck within the cavity of the mould, again making this revision unusable.

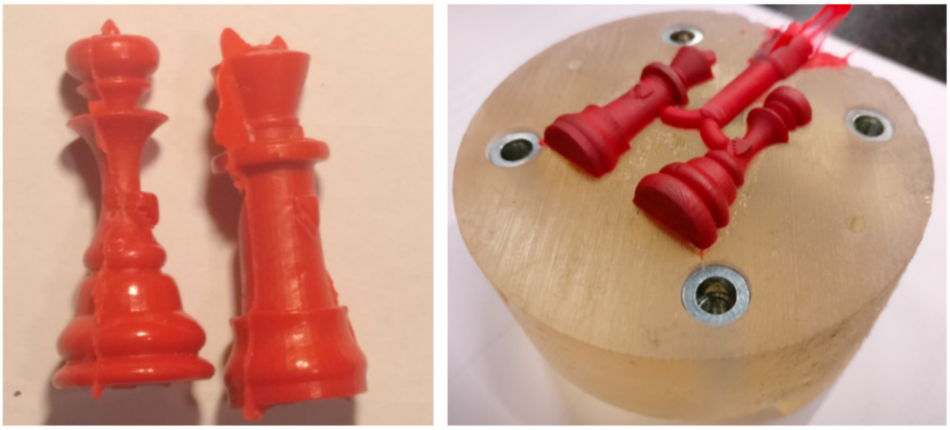

Fig. 5. (a) Revision 1 displayed excessive levels of flash. (b) Revision 2 failed to eject components and was limited to only one cycle.

6.2. Clip

The clip example as mentioned in the ‘Testing of Tooling’ section served as a case study as to how to set up an automated injection moulding machine for 3D printed inserts. Therefore the expectation was that any good product to come from this test would render this test a success. After multiple cycles of bad product which included short shots and flash, twenty good shots of components were produced with the most minor of surface blemishes, often caused by the layer lines of the mould. The success was short lived as after twenty shots, the mould began to fracture around the more narrow section of the cavity. It was determined that this fracture was caused by the sprue insert which protruded past the parting line of the mould by approximately 0.1mm and would not compress when pressed against the plastic causing the insert to warp and fracture during clamping loads.

Fig. 6. (a) The MUD setup could produce over twenty components. (b) Fractures began to emerge at the ends of cavities.

7. Discussion

The primary aim of this research was to design, manufacture and test a system capable of accommodating the needs of mass customisation while being a competitive alternative to additive manufacturing as well as traditional manufacturing. The first iteration of design using the desktop injection moulding machine offered some significant learning outcomes on how not to approach this process development. For injection moulding to be truly exploited as a process using additive manufacturing, strong use of automated machines capable of injecting plastic at speed and ejecting fully formed components without the interaction of an operator would be required. At this point a rethink was required to develop a strong collaboration between what had been achieved using these processes to date and what was potentially achievable through further research. Consequently, the design of the master unit die meant that a system could be developed which was able to exploit the benefits of additive manufacturing such as short lead times and low costs for tooling while maintaining the consistency which traditional manufacturing offers such as part geometry, low costs per unit and a superior materials library. Additionally, because the MUD is a one off piece which will be used to manufacture many designs, it means there is a significant reduction in the cost per unit of unique pieces as the cost of tooling is now limited to setup costs, the cost of ejector pins and the 3D printed mould insert, significantly less than a piece of metal tooling and similar to the cost of printing the component the tooling itself is designed to make. The clip and the dog collar components that were produced were, as expected, of a lower surface quality than that of a plastic component produced using a metal mould. The blemishes are not critical, nor are they particularly noticeable, nevertheless they are a unique feature to these components and one that can improved upon with the investigation of post processing techniques to the printed inserts. The failure of the clip insert to last no more than a couple of cycles in the injection moulding machine highlights that tight tolerances and thorough design are not to be taken for granted despite the lower metrology capabilities of additive manufacturing, as these well planned stages can save time and effort when it comes to physically producing parts. The learning outcomes of the chess piece example were key to the success of the clip example, where it was known how to set design the tooling in a more effective manner and not damage the mould before producing product. One of the key improvements which can be made to this process would be to develop a knowledgebase or series of documentations demonstrating and explaining how to set up this process correctly and efficiently.

8. Conclusions, limitations and future work

Overall, the research undertaken here was a strong success. It proved the concept that new age technologies such as additive manufacturing can be added to the wealth of knowledge built up over decades in traditional manufacturing techniques to create new processes focused towards meeting the ever changing needs of the consumer. The quality of product produced using the hand injection method for the chess pieces proved that existing technologies and trades such as toolmaking need to be exploited in an effective manner to avoid encountering many of the defects in injection moulding which have been worked on and overcome in previous decades. The success in producing components using the clip method proved that end products can be produced using this method in an economic and commercially viable manner. However, the low cycle life of the clip insert proved that careful consideration is needed during the design and manufacture of these moulds, otherwise the consequences are a waste of resources and manufacturing time

One such limitation of this research were the products which were chosen to run as case studies. The chess piece example and the clip were not chosen because of their strong market potential, nor were they chosen because of the need to use such a process on them but because their simple design made it easy to design, manufacture and test a mould using this process. Additionally, their standardised design works well at verifying the concept of low volume production, but it does not appreciate the growing need for unique products in the consumer market. Therefore in future studies, a product with varying configurations dependant on the customer's feature selection will be selected and a total economic comparison is to be done between using additive manufacturing, traditional manufacturing and rapid tooling to produce the product.

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