The Application of the Z-Corps 3D-Printing System for the manufacture of Rapid Tooling inserts, for the Production Polymer Injection Moulded Parts.

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ABSTRACT.

This paper investigates the utilisation of Z-Corps low cost 3D printing process to produce direct polymer injection moulding tool inserts for fast low, cost aesthetic components.

Rapid Tooling using rapid prototyping methods such as SLAs' AIM and SLSs' Rapid steel has been used to produce plastic injection mould tools.

The application of 3D printing utilising plaster based materials and hardeners for direct injection moulding is investigated. The investigation focuses upon the feasibility, repeatability, accuracy and moulding process.
The application is to create low cost aesthetic parts in durable engineering polymers directly in hours rather than weeks.

Keywords: Rapid Tooling, 3D printing, Plastic Injection moulding

1. INTRODUCTION

The focus on productivity, short product lifetime, and cost savings has become one of the main concerns of industries worldwide. Industries need to develop and manufacture new products more cost effectively in shorter lead times. The problems of product design and the production of prototypes are significant obstacles to the launch of new products because design iterations add time to the product development process, and prototypes are used to confirm the design and customer requirements. A prototype is a duplicate version of an end product.
To this end, the 3D Computer Aided Design (3DCAD) and various Rapid Prototyping (RP) techniques have been developed to produce physical prototypes in an effort to reduce time to market [1]. Rapid prototyping was once considered as a technology for only the industries such as automotive and aerospace, but it is becoming more commonplace in the government, military, academic institutions, business machines, consumer products, and medical industries[2]. Rapid Prototyping is a technology used for building physical models of a component and prototype parts directly from 3D computer aided design data. The technology is able to produce a part or an object of moderately complex geometry. Also, rapid prototyping facilitates the early detection and correction of design flaws.

The slowest and most expensive step in the manufacturing process is tooling. Since moulds and dies often have complex geometries and require high quality, they are traditionally made by CNC machining, i.e. lathe, milling, grinding, electro-discharge machining (EDM), or by hand all of which are time consuming [3]. Rapid tooling is a natural progression from RP that can build prototype tools directly from CAD models. It is able to reduce lead times and costs for low volume tooling and prototype tooling. At present, rapid tooling has been developing robust

technologies to be used for manufacturing processes such as vacuum forming, die casting, injection moulding, etc. There are many different rapid tooling processes available for producing injection moulded prototype parts, e.g. SLA Aim tooling, SLS tooling RapidSteel, epoxy tooling, Keltool and other processes.
The research focuses up on mould design and also the use of the Z-Corp machine to produce injection mould tooling to manufacture simple 3D and aesthetic 3D plastic parts. The low cost Z-Corp printing machine is able to produce physical prototypes quickly, easily and inexpensively from 3D CAD data.

The investigation looks at the manufacture of a simple part first to establish which infiltrates and manufacturing settings are applicable. The results then being utilised to manufacture an aesthetic 3D component based upon both Northumbria University's logo and the Gateshead Millennium Bridge, this was used to validate the process. To verify the design of the mould tooling, Moldflow Plastics Adviser^{TM} software package was used to predict the quality of the plastic product, also used to analyse the best gate location of the injection sprue, pressure, flow analysis, and temperature in the injection moulding process.

The original definition of Rapid Tooling was "A 3D CAD driven process that generates tooling inserts in a layer by layer process for the production of components in end use materials [4]. Rapid tooling (RT) is a natural extension of rapid prototyping. It originated from the need to assess rapid prototyping models in terms of their performance [5]. It was introduced as a new generation of tool making techniques, and was defined as a technique to produce low volume metal and plastic products from the rapid prototyping process. Rapid tooling is a process that allows a tool for injection moulding and die casting operations to be manufactured quickly and efficiently. It is the ability to build prototype tools directly as opposed to prototype products directly from 3DCAD models resulting in compressed time to market solutions. RT offers a high potential for a faster response to market needs, creating a new competitive edge. In addition, the rapid tooling process provides higher quantities of models in a wider variety of materials. The purpose of rapid tooling is not the manufacture of final parts, but the preparation of the means to manufacture final parts [6].

Rapid tooling can be divided into two methods, which are indirect and direct. The indirect process is a method that requires a pattern, typically produced from a rapid prototyping system, to create the tooling inserts. The direct method produces the inserts from a rapid prototyping system without an intermediate process.

Indirect rapid tooling is a method that uses rapid prototyping master patterns to create moulds or dies. This method can be used for production of both plastic and metal, for example, injection, vacuum casting, blow moulding, extrusion, sand casting, investment casting, sheet metal forming, etc. Indirect rapid tooling can be divided into soft tooling and hard tooling.

Soft tooling can be obtained via replication from a positive pattern or master. The alternative definition is based on the rigidity and durability of the tooling [5]. It is possible to define soft tooling by the method and material of manufacturing, such as silicone, epoxy, wax, low melting alloys, etc.

Hard tooling is often referred to as that made from hardened tool steels processes such as Keltool Tooling, Cast Metal Tooling and Electroformed Tooling.

Direct rapid tooling is aimed at the realization of production tooling directly from CAD data files, with the smallest possible number of operations [6].

- Direct AIM: A technique from 3D systems in which stereolithography produced cores and cavities are used, with traditional metal moulds for injection moulding of high and low density polyethylene, polystyrene, polypropylene and ABS plastic [7]. Tools can be produced within 2 to 5 days with good accuracy.
- LENS/Laser Generating: Sandia developed Laser Engineered Net Shaping; LENS involves blowing powder into a molten pool, a laser beam melts the top layer of the part in areas where material is to be added. Powder metal is injected into the molten pool, which then solidifies. Layer after layer is added until the part is complete [7]. This technique offers fully dense parts, since the metal is melted, not merely sintered. There are varieties of metals including stainless steel, tool steel, titanium carbide cements, etc.

- SLS/DTM/RapidSteel: DTM sells a steel powder; coated with a thermoplastic binder. A product is built by melting the thermoplastic with a 50W laser [8]. DTM process is used to produce a metal mould for injection moulding. RapidSteel can also be used for pressure die casting of metals.

Why use the Z-Corp 3DP process – the Z-Corp 3DP has one of the highest build rates of any rapid prototyping machine, it allows users to produce three-dimensional conceptual models of any complexity directly from CAD data, quickly and inexpensively [9]. The technique creates models by printing a binder onto individual thin layers of powder. An ink jet printer head lays binder solution to a controlled thickness of material such as starch powder, plaster, ceramic, etc, representing a slice through the 3D computer model of the part.

The main disadvantage of the system is poor accuracy of parts built. The accuracy of the system depends on the material that is used and is affected by binder seepage, shrinkage, and geometry. In addition, the models produced are not particularly strong in tension especially without infiltrates, but compressive strength is high. The surface quality of prototypes from the 3DP process is not high, a smoother surface can only be obtained by post processing.

Injection moulding is one of the most common processing methods for polymers. The injection moulding process is a complex process that involves a series of sequential process steps. The different phases of the injection moulding process include the mould filling phase, the packing phase, the holding phase, the cooling phase, and part ejection. Solid plastic is melted, and the melt is injected into the mould under high pressure (usually between 10 and 34.5 MPa) [10].

2. RESEARCH METHODOLOGY

2.1 Research Goal

The goal of this research is an investigation into the use of Z-Corp 3D printer machine for sample plastic production. The method for this investigation can be divided into five stages.

1. Concept generation and 3D CAD model
2. Using rapid prototyping for part checking
3. Using Moldflow for injection mould analysis
4. Create mould tool design from 3D CAD
5. Using Z-Corp machine to build mould tool

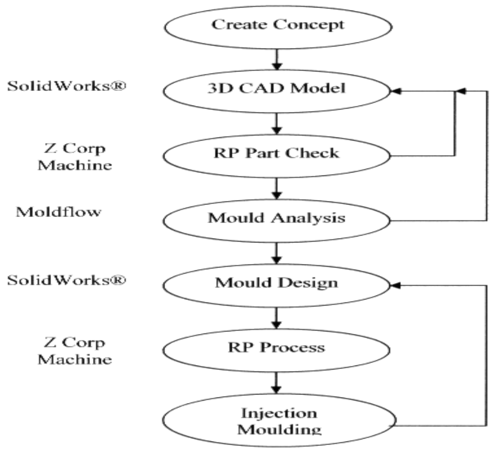

Figure 1: Research Methodology

Stages 1 to 3 were undertaken to design, accurately manufacture and validate the test mould tooling for the sample parts and the desired design component as per Figure 2. Two infiltrates, cyanoacrylate and paraffin wax, were investigated.

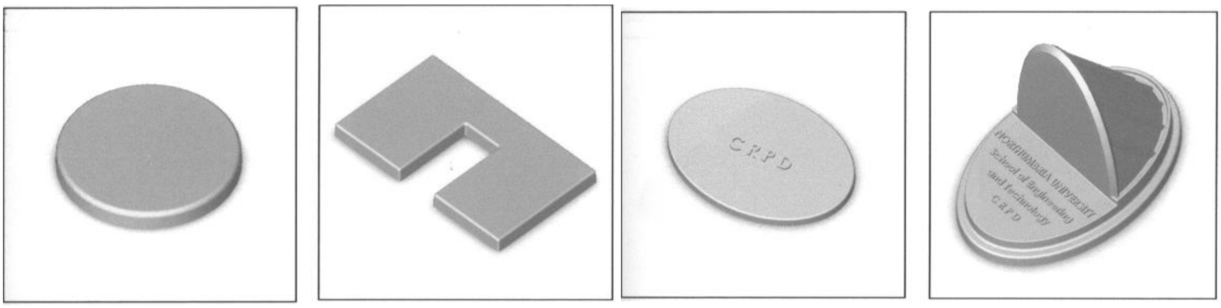

Figure 2: 3D design of cylinder, U shape and ellipse test pieces and Millennium Bridge.

The finished parts of the rapid prototyping process were then measured by digital vernier calliper, to identify any errors in build accuracy. From the measurements, the parts built from 3DP process were bigger than the original 3DCAD model dimensions by 1.63%. To solve this problem the anisotropic scaling factor was changed from 100% to 98.37%.

Plastic flow analysis involves an investigation of best gate location, flow analysis, confidence of fill, quality prediction of the parts as per Figure 3.

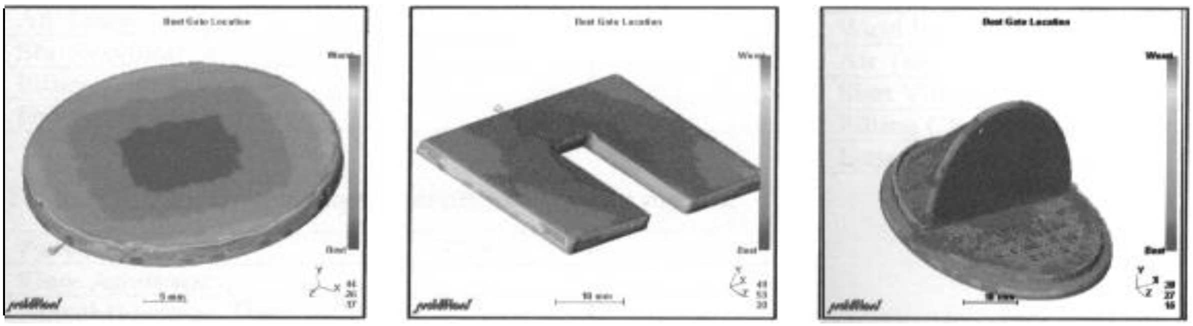

Figure 3: The best gate location analysis, Circular model, U shape and Millennium Bridge

The Mould tools were then designed to fit the manimould process and the bolster manufactured to support the 3DP inserts as per Figure 4.

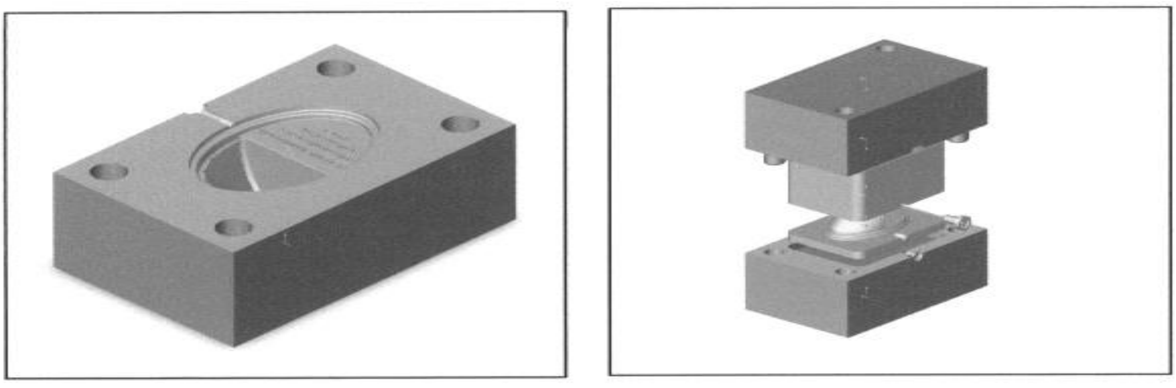

Figure 4: Mould tool design of mould (female) and total tooling for Millennium Bridge

2.2 Mould Tool Production

The material used to create the mould tool is plaster-based powder ZP100. The setting of the Z402 machine is shown as follows:

- The build layer thickness 0.1 mm
- Binder shell saturation value 2
- Binder core saturation value 1
- Anisotropic scaling factor 99.63% for X, Y, and Z-axis

The wax infiltration was undertaken by using the ZW4 autowaxer, the part was preheated for 30 minutes, 5 second dip, and 15 minutes post heated. The cyanoacrylate penetration was undertaken by dripping the material onto the moulds. Figure 5 shows the sample of mould produced by the Z-Corp printer.

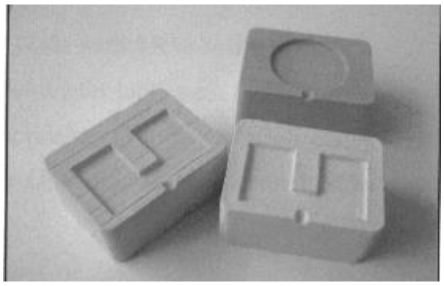

Figure 5: Mould tool produced by 3DP U shape and Cylinder (female)

2.3 Injection Moulding

In this experimental test, the injection-moulding machine used to produce the plastic product is "Plunger injection machine" Manimould. The temperature at barrel was set at 200^0C and the temperature at barrel head was set at 180^0C. The thermoplastic used polystyrene with a melt temperature of approximately 200^0C.
The melt is forced into the mould through the injection nozzle of the injection unit. This operation is known as the shot rate. This shot rate can also refer to the pressure of the process. In this research, shot rate and various pressures are controlled in order to know the suitable shot rate and pressure for the Z-Corp mould tools.

From the injection nozzle, the material passes through the sprue bush of the mould. It is then distributed to the cavities. When the cooling period has elapsed, the mould is opened and the finished parts are ejected.

The experimental test can be separated into two sections, which are:

1. Z-Corp mould tools with cyanoacrylate (ZR10) infiltration
2. Z-Corp mould tools with paraffin low melt wax infiltration

The different features of the Z-Corp mould block (Circular, U shape, Ellipse, and Gateshead Millennium Bridge) are tested with the different shot rate and various pressures. The shot rate used in this research can be divided into 2 shots, 1 shot, 3/4 shot, 3/5 shot, and 1/2 shot. Various pressures are used to force the melt material into the Z-Corp mould. The temperature is set in the range of 180^0C to 200^0C.

3. RESULTS AND ANALYSIS

3.1 Z-Corp Mould Tools with Cyanoacrylate ZP10 Infiltration

Z-Corp mould tools used in this experimental test had improved surface quality and strength by using cyanoacrylate (ZP 10) or super glue infiltration. The tests covered the quality of the finished part, and impact of the injection moulding conditions against the mould tools. The injection moulding results were divided into the ranges of F (part Failed), n/f (filled short part), A (Acceptable), and S (Satisfactory). The tests were divided into the four types of model parts to be manufactured, only the simple cylinder and bridge designs evaluated in this paper.

1. Test 1: Cylinder Model

Test	Temp of Head ^{0}C	Temp of Barrel ^{0}C	Temp btw Head and Barrel ^{0}C	Pressure MPa	Shot Rate	Result
1	193	198	160	4.96	2	F
2	193	198	160	4.55	1	F
3	193	197	160	4.20	3/4	F
4	195	197	165	4.06	1/2	A
5	195	198	165	2.75	1/2	n/f
Note: F = fail, A = acceptable, n/f= not full						

Table 1: The summary results of the injection-moulding test 1.

The results of tests 1 to 3 were “fail” due the quality of the finished parts being unacceptable, as the plastic parts were over flowed and material pierced into the mould tool. This was due to the high pressure and over shot rate. The quality of the finished parts of test 4 was acceptable, and shape of the models was good. The accuracy of the model of test 4 for the diameter was 38.95 mm compared to design of 38.7 mm, error 0.64 %, and thickness 5.09 mm compared to design of 3 mm.

Even though the shape of the finished parts was acceptable, the surface quality was not good. The surface quality of the finished part was dependent on the surface roughness of the Z-Corp mould. Part ejection is a major problem of this test. The finished part was very difficult to ejected since the plastic was stuck on the mould; therefore the method to take the part out is to break the mould apart.

Similar results were recorded for the other test tools, and a shot rate of 3/5 providing an injection pressure of 4.17 MPa was used to produce the bridge components Figure 6.

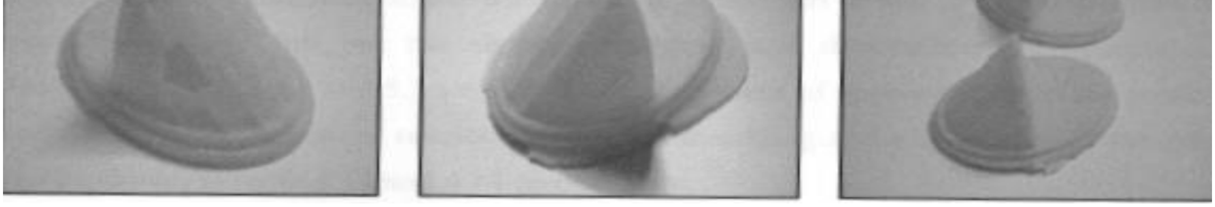

Figure 6: The finished “cyanoacrylate” part of Gateshead Millennium Bridge model.

3.2 Z-Corp Mould Tools with Wax Infiltration

In this test, mould tools produced by the Z-Corp printer were infiltrated by using paraffin low melt temperature wax. This study covered the quality of the finished part, affect of temperature, pressure, and shot rate against the mould. The experiment was divided into four tests according to the features of the mould block.

1. Test *5:* Cylinder Model.

Test	Temp of Head (^{0}C)	Temp of barrel (^{o}C)	Temp btw Head and Barrel	Pressure (MPa)	Shot Rate	Result
T5.1	197	198	165	3.5	1/2	A
T5.2	197	198	165	3.93	1/2	S
T5.3	197	198	165	3.93	1/2	S
T5.4	197	198	165	3.96	1/2	A
T5.5	197	198	165	4.27	3/5	F
Note: A = acceptable, S = satisfactory, F = failed.						

Table 2: Summary results of injection moulding of test *5.*

From the injection moulding tests, the plastic parts of mould with wax infiltration are more acceptable than the finished part from mould compared with cyanoacrylate penetration. The characteristics such as shape and roundness of the parts were superior and ejected easier, Table 2 refers to the cylindrical parts, other test moulds yielded similar results. Figure 7, the Gateshead Millennium Bridge, it can be seen that the products have plastic flash at the split line. Therefore, the parts require post processing to improve the quality and shape of the finished part.

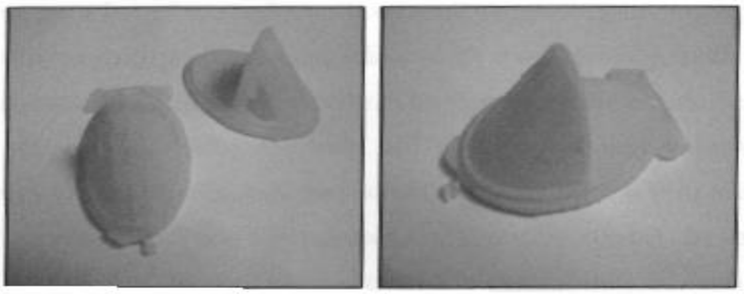

Figure 7: Sample picture of product from test 8.

4.0 CONCLUSIONS

In this research, the Z-Corp 3D printing machine was used as a rapid prototyping technique to produce sample plastic parts. The focus of this study was on the part design, mould design, creation of sample part and mould tool using a Z-Corp 3DP machine, injection moulding process, and injection moulding conditions.

The prototypes and mould tools had improved surface quality and strength by infiltration with cyanoacrylate and wax. The 2D and 3D parts were measured and checked for detail and dimensional accuracy, and the anisotropic scaling factor was changed to improve accuracy.
It can be concluded that injection pressure played a significant role in the process. Too high or too low injection pressure had a major effect up on the finished parts, such as over filled “flash”, short filled, distortion, sink marks, warpage, etc. The pressure also affected the dimensional accuracy of the finished parts, too high injection pressure resulted in increased part thickness.

Temperature has little effect on the finished part and mould tool. This is because the mechanical properties of the plaster base powder and infiltration method can resist high temperature. However, high melt temperature can cause problems with part ejection and shrinkage in the mould.

Infiltration material was also a factor that has an influence on the part ejection and surface quality of the product. The surface quality of the product produced by wax-infiltrated mould was better than on the product manufactured by superglue infiltrated mould. Part ejection was the major problem of the Z-Corp mould with cyanoacrylate infiltration, as the plastic product reacted with the mould cavity material. The high temperature of injected material melted the cyanoacrylate to liquid, therefore, the part was adhered to the mould. Mould tools had to be destroyed in order to take the finished part out of the mould.

The accuracy and surface quality of the finished part were quite low due to the Z-Corp printing machine. Complexity of the part also had an effect on the quality of the finished parts. It was seen that simple models are easily manufactured when compared with the Gateshead Millennium Bridge model.

Circular and U shape models have higher quality than the Ellipse and Millennium Bridge models according to the complexity.

In this study, it was found that plastic parts manufactured by Z-Corp mould are acceptable, but still need post processing to improve the accuracy and quality. The Z-Corp rapid prototyping technology can be used as a mould tool to produce plastic parts. However, this manufacturing technique is not suitable for complex geometry or delicate products. This technology is more suitable for a simple product or a part that doesn’t require high accuracy.

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