Fabrication of mandible fracture plate by indirect additive manufacturing

M Aizat and S F Khan
Mechanical Engineering Programme, School of Mechatronics Engineering, Universiti Malaysia Perlis (UniMAP), Pauh Putra, Perlis, Malaysia.

sfkhan@unimap.edu.my

Abstract. Bone fracture is a serious skeletal injury due to accidents and fragility of the bones at a certain age. In order to accelerate fracture healing process, fracture bone plate is use to hold the fracture segment for more stability. The purpose of this study is to fabricate mandibular fracture plate by using indirect additive manufacturing methods in order to reduce time taken during bending and shaping the fracture fixation plate that conform to the anatomy of the fractured bone site. The design and analysis of the plates are performed using CATIA and ANSYS software. The 3D-CAD data were sent to an additive manufacturing machine (fused filament fabricated) to generate master pattern using PLA and the mould were fabricated using Plaster of Paris. A melt ZAMAK 3 was poured directly into the moulds, and left it until completely harden. 3point bending test was performed on the prototype plate using universal testing machine. Stress-strain curve shows the graph exhibited a linear relationship of stress-strain up to a strain value of 0.001. Specimens give a maximum yielding stress and then break before the conventional deflection. Since the maximum flexural stress and the breaking stress are far apart with a plateau stating at strain value of 0.003mm/mm in most specimens, the specimen’s failure types are considered plastic failure mode. The average thickness and width are 1.65mm and 2.18mm respectively. The flexural modulus and flexural strength are 189.5GPa and 518.1MPa, respectively.

1. Introduction
In order for a fracture to heal, the bones must gently to be fixed in suitable position and strong enough to withstand body weight and protected [1]. The fracture plate or bone plate is designed for numerous bone fractures, osteoporosis, and other musculoskeletal problems caused by accidents or natural at specific ages. This problem need to be solved by using temporary, permanent and biodegradable fracture plate. The role of fixation plate is to hold fractured bone segments in the correct position without allowing the tensile stress at fracture face but have some critical compression stress caused in it to speed the healing process [1]. However, most of the available fixation plates are standardised that do not fit conformably to the fracture site. Intraoperative bowing of plates can be tedious. Twisting reproduction plates relies on upon the multifaceted nature of resection and specialist's expertise. However, by fabricating the desired plates according to the structure of the fractured site using additive manufacturing technologies as oppose to bending the plates on the 3D models before the surgery will reduces operating times [2,3]. Lethaus et al used the technique of AM on 20 case studies that required mandibular resection and reconstruction because of a tumour or osteoradionecrosis. The average time to bend a plate on a non-sterile model was 0.42 hour (range 0.25-0.68 hour) and can reduce operating surgery time up to 1.4 hours [4]. Additive Manufacturing (AM) is a suitable name to
represent the innovations that produce 3D artefacts by stacking successive layers of materials including plastic, metal, and concrete. Common to AM systems is the utilization of a computer, 3D modelling software (Computer Aided Design or CAD), machine hardware and layering material. Once a CAD sketch is produced, the AM equipment reads in data from the CAD file and lays downs or adds successive layers of liquid, powder, sheet material or other, in a layer-upon-layer fashion to fabricate a 3D object. The approach in producing artefacts using AM techniques is the opposite of subtractive manufacturing processes. Many design guides have been developed for these subtractive processes. However, when designing artefacts that are to be manufactured by utilizing AM as the manufacturing process, designers need a different approach. Most AM systems have the benefits of freedom in geometrical shape definition as well as tooling independent. Conventional manufacturing’s cost is highly dependent to the geometry complexity, therefore with lower cost combined with design freedom; both manufacturer and customer will benefit. With the help from AM, designers have unrestrained freedom to design for customization rather than to design for manufacturing and assembly. Therefore, products can be designed to fit the user rather than the other way around [5].

2. Methodology

2.1. Materials
PLA was used in this research in a form of master pattern because it easy to melt during to eliminate from mould casting made by Plaster of Paris (POP). In order to fabricate prototype plate, ZAMAK 3 is used in this research as alternative material to obtain the material strength and mechanical properties.

2.2. Equipment
A fused filament fabrication (FFF) 3D printer was used in this research to generate master pattern. A gas furnace was used to heat ZAMAK 3 into molten form before pouring into the created mould. This will generate metal prototype plates. A universal material testing machine was used to conduct flexural tests on the prototype plate specimens.

2.3. Design of Experiment
Figure 2.1(a) shows the intended design of the fixation plate with sprue and air vent required during molding process. The master pattern of mandibular fracture fixation plate was design by using CATIA V5R16. When the design is completed, the plate was analysed using ANSYS Workbench 14.5 to determine which plate are the best. To print out the plate, industrial polylactic acid (PLA) polymer was utilised as the built material in fused filament fabrication (FFF) printer. The melting point of PLA is between 180°C – 220°C [5]. Figure 2.1(b) show the orientation of the printed part during 3D printing. The time taken to print out the master pattern is 44 minutes. In order to get the precise dimension of the plate, the percentage of plate thickness is increase to 40% due to shrinkage that occurs during printing.

![Figure 2.1 Design and fabrication of master pattern.](image)
2.4. Casting Process
Plaster of Paris (POP) powder was used in this process in order to the casting mould that will produced the prototype of mandibular fixation plate. POP can be executed at room temperature and the maximum working temperature of POP is 1200°C [6]. Therefore, the setting process of POP can be made by mixed the powder of POP with water. The plaster is then poured over the master pattern (PLA) into the container provided. The container can be removed after 20 minutes. The process is repeated to produce the second piece of mould base. The casting can be seen in figure 2.2 (a). In order to remove the PLA master pattern, gas furnace was utilized to melt the PLA at 250°C for 7 hours to completely removed the PLA. Figure 2.2 (b) and (c) shows the process of melting the master pattern and the expected mould that was created to pour ZAMAK 3 in the next stage.

![Figure 2.2 Casting result (a), Eliminate of master pattern (b), and Expected mould (c).](image)

2.5. Fabricating Prototype Plates
ZAMAK 3 was heated by using gas furnaces. The furnaces temperature was set to 384°C to melt the ZAMAK 3 within 30 minutes [7]. Once the ZAMAK 3 is melted, the pouring process can be executed. The two pieces of the mould were place in a container that is filled with soil as shown in figure 2.3(a) before the pouring process is performed. The pouring process of ZAMAK 3 into the mould as shown in figure 2.3(b) must be perform within 10 seconds to maintain ZAMAK 3 flow ability and avoid the melt to thicken. It takes 30 minutes to completely solidify and cool down before the mould can be broken to get the desired physical plate as shown in figure 2.3(c). The physical plate need to undergo finishing process by using grinding and drilling machine as shown in figure 2.3(d) to eliminate unwanted sprue and vents as well as to get a smooth surface.

![Figure 2.3 Expected mould (a) Poured process (b) Physical plate before finishing process (c) Physical plate after finishing process (d)](image)
2.6. Flexural Test

Flexural test was conducted to evaluate the force needed to bend a beam under three point loading conditions by using a universal testing machine (UTM) according to the ASTM D790 standard as shown in figure 2.4 [8]. The test was conducted using a load cell of 150N with loading speed of 1mm/min. When the specimen breaks, the test was stopped. In order to obtain a satisfactory result, five specimen plates were tested by taking their average of the collected data.

![Figure 2.4 Bending test diagram and the actual test on a universal testing machine rig](image)

3. Result and Discussion

In total, five tests of specimen plates are fabricated from ZAMAK 3 and casting mold that has cavities measuring 1.5mm x 2mm x 44.7mm each. All measurements for ZAMAK 3 specimen plates were taken and the range of thickness and width for the specimens are from 1.5mm to 1.8mm and 2.0mm to 2.3mm respectively.

The overall length is 45mm for all the specimens and the span length in the three points bending test is 50mm. The mechanical test is based on 3-point bending testing procedure of ASTM D790 and was conducted for all 5 specimens. The results are as shown in figure 3.1 and table 3.1.

From figure 3.1(a) and (b), the graph exhibited a linear relationship of stress-strain up to a strain value of 0.001. Specimens give a maximum yielding stress and then break before the conventional deflection. Since the maximum flexural stress and the breaking stress are far apart with a plateau stating at strain value of 0.003mm/mm in most specimens, the specimens’ failure types are considered to be plastic failure mode. The fracture images are as shown in figure 3.3. The reason why specimen at T3 has such a large deflection and strain as compare to the others 4 specimens is because the thickness of that specimen is higher.

![Figure 3.1 Stress-Strain curves of ZAMAK 3 plates](image)
As shown in table 3.1, there is no significant variation in terms of dimensions and mechanical properties of ZAMAK 3 test specimens using the fabrication process. The confidence interval in repeating the manufacturing of the specimen is as calculated using t-test with p-value <0.05. The average thickness and width are 1.65mm and 2.18mm, respectively. The flexural modulus and flexural strength are 189.478GPa and 518.138 MPa, respectively.

### Table 3.1 Mean value for 95% confidence interval for casting test samples of ZAMAK 3 plates.

| Dimension       | Max. Flexural Load Fmax (N) | Flex Strength (MPa) | Flex Modulus (GPa) |
|-----------------|-----------------------------|---------------------|--------------------|
| Thickness (mm)  | 32.34±9.11                  | 518.14±154.12       | 189.48±77.79       |
| Width (mm)      | 1.65±0.14 2.18±0.13         |                     |                    |

The result of ANSYS analysis was indicated in figure 3.2. The maximum result is label by red region while the minimum result is label by blue region. The mesh sizing is defined as 1mm this simulation. The maximum deflection is 0.27807mm when load 150N is applied on the midspan of the specimen as indicated in figure 3.2(a). The maximum stress is 364.96MPa as indicated in figure 3.2(b). The percentage error of maximum flexural strength between experimental and theoretical of ZAMAK 3 plates is 41.97%.

![Deflection result after load applied](a)

![Stress result after load applied](b)

**Figure 3.2** Deflection result after load applied (a) Stress result after load applied (b)
In order to understand further the behavior of ZAMAK 3 during three points bending test, images are captured at 100X magnification by using scanning electron microscope (SEM) at bending fracture failure surface. Images also showed the porosity region A and material consolidation region B experiencing ductile failure (crystal-like surface) as indicated in figure 3.3. There are two causes of porosity that occur during casting process such as gas formation and solidification shrinkage.

Large gas related voids caused by trapped mold or core gases in the molten metal are called blows or blowholes. They generally are large enough to look like bubbles with smooth interior surfaces and are always buoyant and will float near the top of the casting, as it was oriented in the mold. Shrinkage related casting voids are caused by sections of the casting that solidify later than the surrounding sections and do not have enough metal flow into the section for a complete fill. This is generally because the area is too hot for too long due to a thick section or a tight corner.

Figure 3.3 Fracture of ZAMAK 3 plates obtained from bending test showing the region of tension.

4. Conclusion
In this research, the prototype plate was performed by using indirect additive manufacturing method in this experimental. By using mould created from FDM or FFF, the cost of mould can be reduced as AM fabrication cost is not exponentially related to part complexity. Through this method, it can provide low cost of producing the plates if compared to rapid manufacturing methods.

The application of ZAMAK 3 in this experimental is to evaluate the dimensional accuracy and repeatability of using indirect additive manufacturing method to fabricate fracture plate and to understand the effect on the material strength and mechanical properties of the material. To apply ZAMAK 3 material in implant surgery are not relevant because the corrosion and weak of the strength if compared to Titanium. It is costly to perform this experimental by using Titanium material.

In term of customizing the fracture fixation plate, the plate can be design based on acquired data from CT scan. Thus, reduce the time taken by high skill of surgeon to customize the plate during surgery rather by conventional methods.

Definitely to produce mandibular plate in fixation treatment can be achieved by using indirect additive manufacturing method without spend a lot of money in producing by using EBM machine just to fabricate a small part. Besides that, this indirect additive manufacturing method also can be applied in other engineering field such as automotive field.
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