Additive Manufactured Continuous Fiber Composites in Tooling

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Abstract. Tooling plays a critical role in the accuracy and precision of the produced parts in manufacturing. Certain established parameters need to be followed while designing the tools. The choice of material, geometry, tolerances, and surface finish of tools depends on the application. 3D printed parts with continuous fiber were used in aerospace, as functional parts. But at present, the printers can only print a few materials supplied by "OEM". To take the advantage of high strength and high stiffness open source materials, tools were printed in the 3D printer and thermoset composite components were made with open source carbon, glass fibers with epoxy resin. When time is shorter, quantity requirement is less, the component has complex features and application demands high strength and high stiffness, then '3D printed tools' is one of the solutions for such problems. This paper explains the tooling for different manufacturing methods, principles involved in tool design and applications of 3D printed continuous fiber composites in functional tools. Materials used for tools were high strength high temperature glass (HSHT), carbon fibers and onyx polymer. Matched-die mould tool, drill jig and tool for 3D preform were successfully printed with complex features, exploiting the advantages of 3D printing. Holes with high aspect ratio, complex internal and external geometrical features, unconventional location and supporting features were printed which are difficult in conventional manufacturing. FEM analysis was carried out to reduce the quantity of costly printing material.

Keywords: Functional tooling · Continuous fiber · 3D printing · STL file · Location · Tolerances · Mould · Jig and FEM

1 Introduction

Depending upon the type of manufacture, there are several different types of tools. They are used in metal manufacturing, composite manufacturing, ceramics manufacturing and elastomers manufacturing. They include machining fixtures, drill jigs, casting tools, forming tools, welding fixtures, filament winding mandrels, compression moulds, investment casting tools, matched-die moulds, open mould tools, bonding fixtures, extraction fixtures, assembly fixtures, inspection gauges, testing fixtures and material handling

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tools. Depending upon the type of tool to be designed, tool material, condition of material, prismatic shape and standard sizes are chosen. In metal, steel with different compositions of carbon and alloying elements with several different material conditions are used. Sometimes aluminum, brass and invar are also used. In composites neat resins, particulate composites, short fiber composites, and continuous fiber composites are used as tools. Tooling pre-pregs also available for making tools. Sometimes ceramics are also used for tools. In some applications elastomers are used as pressure pads and inflatable mandrels. Sometimes combination of above materials is used in tooling. In additive manufacturing, we can print functional tools directly. The application spectrum has been increasing further with the 3D printing of continuous fiber composites. At present in addition to functional parts and prototypes, 3D printed parts are in use in many tooling applications including matched die moulds, drill jigs, tools for making preforms, machining fixtures, compression moulds, injection moulds, robotic grippers, patterns in casting, forming tools, inspection fixtures and gauges [6, 7, 8]. In tooling proper location, clamping, supporting and guiding of tool plays a critical role in addition to maintaining required geometrical tolerances and finish. This paper deals with the principles of tool design, tool manufacture and the first article try-out of 3D printed tools. It specifically explains the details of 3D printed matched die moulding tool, drill jig and tool for 3D preform with carbon fibers, HSHT glass fibers and onyx materials using Markforged-X7 3D.

2 Literature Survey

Location, clamping, supporting along with other essential parameters were elegantly explained in reference [1] by E K Henricksen. Nonstandard clamping methods were enumerated by H.E. Granth in reference [2]. ASME Y14.45 [3] explains dimensioning and tolerancing principles for manufacturing. ASME Y14.46 [4] explains the principles and glossary of the 3D printed part. Reference [5] explains materials, methods and qualification of additive manufactured parts. Markforged X7 3D printer was used for printing tools and their user manual [5] explains about printer, software, operation and troubleshooting of the printer. References [7], 8 and [9] explain about the current trends in additive manufacturing and their applications in several different areas. Though there are large size (13mX3m) printers [6] available for printing discontinuous fiber composites in market, for continuous fibers the size is very small. With markforged-X7 3D printer the size of the job is within the build volume of 330mmX270mmX200mm. Continuous fiber composite tools were printed within this build volume. Large tools like mandrels, autoclave cured formats comprises of both egg crate and top plate structures, bigger size moulds were also reported in literature [6] with discontinuous fibers.

3 Development of Continuous Fiber Composite Tooling

3.1 Configuration of Tool

The primary step in the tool design process starts with the analyzing the quality assurance plan of the product, which comprises the details of material, shape, size, tolerances requirement, surface finish requirement, inspection and acceptance criteria. A properly designed tool should accomplish its intended objectives, the result of which is acceptable products. After identifying the objective of the tool, the next step is to identify the surfaces of the product for location, supporting and clamping. In general, planar surfaces are preferred. If plane surfaces are not available, then regular features like cylindrical holes/bosses are taken. Taper and irregular features are least preferred and only considered if others are not available to avoid errors in taper location. The 3-2-1 principle is followed for positioning the object with respect to the cutting tool. 3-2-1 location arrests all six degrees of freedom of object. Due to the ease of producibility of complex geometrical features in 3D printing, Non-standard methods of location, supporting and clamping [2] can be used to fix the component by arresting all six degrees of freedom. If the object has an irregular complex surfaces, the true geometrical counterpart can be produced on 3D printed tools very easily compare to conventional tooling. Size tolerances and geometrical tolerances like form, orientation, location and runout tolerances requirements need to be understood properly before designing the tool. Sometimes there is a need to compensate thermal mismatch of materials, if it is beyond the acceptable tolerance band. Usually the tolerance on the tool is 50 percent of the tolerance on the component. This paper explains three categories of 3D printed tools namely matched die mould, drill jig and tool for making 3D preform.

In the matched die mould (Figs. 1 and 2), the objective was to produce thermoset composite components with open source reinforcements and resins. The requirement was the moulding of component with features like holes, slots, bosses, and irregular contours with stringent geometrical tolerances. This mould comprised of locating holes/pillars with H7/f7 fit for aligning the top and bottom halves of the mould. Ejector hole/pin with H8/e8 fit was provided for ejecting the moulded component. It also had a core for producing a cylindrical hole in the component. Handling and clamping features were provided. Sufficient wall thickness and edge thickness were provided for stiffness and strength.

In drill jig (Fig. 3) the objective was to produce holes on a complex shaped object at desired location with specified size and position tolerances in the direction normal to the local surface. The replica of the surface of component was modeled and produced in 3D printing. The jig was cage type and split for ease of loading/unloading the job. The bottom and top plates were located using dowel pin and a locking contoured feature (unconventional). The 3-2-1 principle was used to arrest 6 degrees of freedom of the component. Modular inserts were provided in the vicinity of holes to give support to the component and for replacement as and when worn out.

In the tool for making 3D preform (Fig. 4), the requirement was the development of 3D preform with third axis reinforcement, the direction of which is normal to the local surface. The geometrical counterpart of the 3D preform, with sufficient thickness was modeled in CAD software and holes were provided in the desired local normal direction. The hole size was 1 mm diameter and maximum depth was 28 mm which was usually difficult in conventional drilling process. But in 3D printing it was printed.

3.2 Material Selection

There are three sources for mechanical properties of the 3D printed materials. They are In-house generated, OEM (Markforged) data sheet and from the literature. This data was used in analysis of 3D printed parts either in functional or in tools. Markforged-X7 3D printer was used for printing of tools. The materials that printer can print are onyx, onyx FR, onyx ESD, nylon, precise PLA, carbon fiber, carbon FR, glass fiber and kevlar fiber. For high temperature applications HSHT material, one variant of glass is available. Usually the maximum temperature with the printable material is up to 140 degrees centigrade due to the thermoplastic polymer(Onyx). With carbon fibers the strength achievable in fiber direction is about 750 Mpa. FR grade materials are useful in fire retardant applications. With the other printer we can print ultem 1010 which can withstand up to 200 degree centigrade but its strength is only 70 MPa. For high stiffness requirements carbon fiber is preferred and for high toughness applications kevlar is preferred, for moderate stiffness and strength applications glass and HSHT glass are preferred and for non-load bearing applications onyx is preferred. Only Onyx, HSHT glass and carbon fibers were used for present tools.

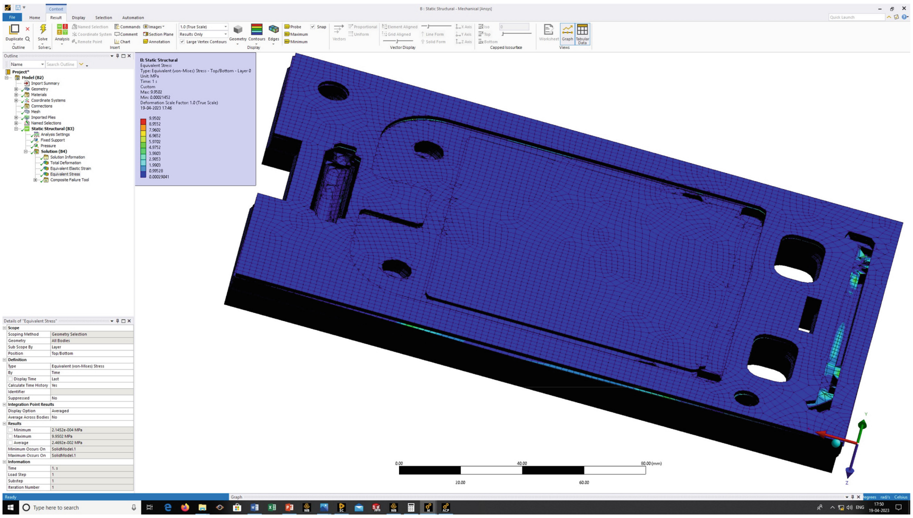
3.3 Model Generation and Slicing in Software

In the case of mould, features like locators, clamps, cores and ejectors were modelled around the component and mold was designed. Some weight reduction features were also provided. In the case of jig, cage type of jig with proper location, clamping and tool guides were modelled around the irregular shaped object upon which the holes were to be drilled. In the case of preform tool, the counter features of desired preform were modelled along with surface normal holes for third direction reinforcements. STL files were generated for models with few micron accuracy of surface profile, and subsequently sent to the EIGER, a 3D printer software. Proper orientation of the job to get reinforcement in the desired direction, brim, and support build angle were selected. In addition, proper material, layer thickness, fiber orientation, fill pattern and fill density were selected based on the requirement and a print file was generated. The print file was sent to the Markforged-X7 3D printer. Since 3D printing material is costly, especially continuous carbon fiber, it is desirable to reduce the consumption.

Representative FEM analysis was shown for matched die mould, for typical layup pattern. This analysis is useful in optimizing consumption of costly material (Fig. 1).

3.4 Printing and Post Finishing

Print bed levelling, the gap between nozzles and bed, and nozzle offset were set properly in addition to Z-axis alignment before starting the job. Nozzles wear, feed tubes, bowden tubes condition were checked prior to the start of print job. Materials both fiber and polymer were loaded as per the requirement. Layer thickness was 125 microns and number of layers depend on thickness of the component. The print file was executed and printing was carried out. The support material was removed. Cleaning of debris if any was carried out. Metallic bushes were fit in to the corresponding holes in the jig for reliable and consistent guidance of the tool bit. Figure 2 shows printed mould. Figure 3 shows printed parts of jig. Figure 4 shows the tool for 3D preform.



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Custom
Max: 9.9502
Min: 0.00021452
Deformation Scale Factor: 1.0 (True Scale)
19-04-2023 17:46

9.9502
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Details of "Equivalent Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Sub Scope By	Layer
Position	Top/Bottom
Definition	
Type	Equivalent (von-Mises) Stress
By	Time
☐ Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
☐ Minimum	2.1452e-004 MPa
☐ Maximum	9.9502 MPa
☐ Average	2.4692e-002 MPa
Minimum Occurs On	SolidModel.1
Maximum Occurs On	SolidModel.1
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	1

Fig.1. FEM analysis of 3D printed Matched-Die Mould

Fig.2. 3D printed Matched-Die Mould

4 Quantitative and Qualitative Information

4.1 Quantitative Information

- With Onyx material, the layer thickness of 50 microns, 100 microns, 125 microns and 200 microns was possible. Surface finish depends on layer thickness and geometry of the part. Surface finish in the order of 0.8(i.e. N6) was achieved with 50-micron layer thickness, on planar surfaces (Fig. 2). Due to staircase effect and higher layer

Fig.3. 3D printed parts of a jig assembly

thickness (200 microns), waviness was observed in tool pertaining to preform (Fig. 4). Due to printer limitation, only 100-micron thick layer was possible with glass and Kevlar, only 125-micron thick layer was possible with carbon.

- More than 50 samples were printed as per ASTM sample sizes and were inspected. 20-micron size accuracy was possible. In functional parts, positional tolerance in the order of 30 microns was observed and profile tolerance was dependent on the orientation of feature with respect to the build direction.
- Component with epoxy resin and Carbon reinforcement was made using matched die mould (Fig. 2). Ejection holes were provided on one of the mould halves. But component was stuck to the other side of the mould. Due to release agent separation between component and mould we could separate the component.
- Bushes with Press fit (p6) tolerance were made and fitted perfectly in to the corresponding holes(H7) in drill jig (Fig. 3).

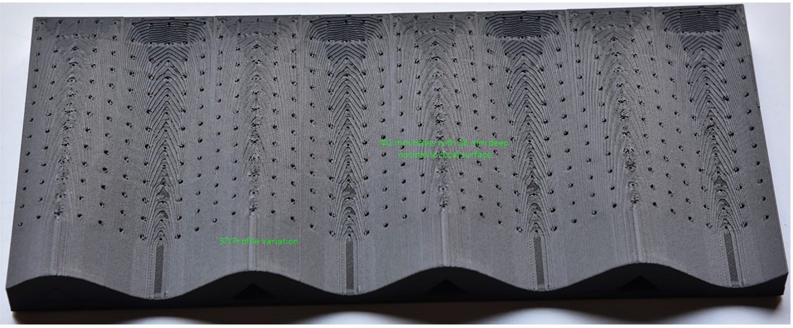

Fig.4. 3D printed tool for 3D preform

4.2 Qualitative Information

- Metal moulds were manufactured for similar components. The manufacturing cycle comprised of raw material selection, heat treatment, welding, stress relieving, machining, plating and surface finishing. For small moulds also, there was a need to run heat treatment equipment which was costly. Where as in 3D printing the mould was printed within two days. With expected frequent modifications and less quantity in requirement, 3D printed moulds are economical.
- Manufacturing of metal jig also had similar cycle mentioned above and in addition making irregular surfaces and holes take additional time, where as in 3D printing time was in days.
- Aligning fiber in load direction reduces material consumption. of the job. If the job size is less and has irregular features, then 3D printing is economical.

5 Conclusion

- Matched die mould was printed and first article try-out was carried out. Ejectors on both halves helps in the smooth ejection of component.
- Drill jig was printed and bushes were fitted. Size and geometrical tolerances on printed jig were within designed values.
- Tool for 3D preform was printed with 1 mm diameter holes, with an aspect ratio of 28. The Layer thickness of 200 microns was used and due to staircase effect in 3D printing the surface was wavy, nevertheless it was acceptable, because it was only for making preform and not final component.
- Open source thermoset composite components were successfully made with moulds.
- If variants are more, batch size is less, and the size of the component is less with irregular surfaces, then continuous fiber 3D printed tools are economical, fast and accurate. on printed jig were within designed values.
- For optimizing consumption of costly material, analysis of tool is helpful, which provides sufficient quantity, with desired fiber direction and layup sequence.

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