Engineering a part for additive manufacturing

Kushal A Jolapara, Srikanth K A, Moinuddin K S

Abstract — Additive manufacturing (AM) has profoundly changed the product design lifecycle, specifically the area of rapid prototyping. This paper presents the use of AM in building different prototypes of products for the defence forces, the engineering problems faced during additive manufacturing and their solutions. The parts showcased were manufactured using Fused-Deposition Modeling, Selective Laser Sintering, Stereo-Lithography and Vacuum casting. To overcome challenges during practical application of AM, certain engineering solutions can be readily applied to improve the functional aspects of parts made using these processes. The objective of this paper is to provide condensed qualitative information on certain design aspects that will help designers who are new to AM technology. Each manufacturing method has intrinsic pros & cons and these became evident during the testing phase. An independent comparison between these processes, based on the parts manufactured, is also presented.

Index Terms — Rapid prototyping, additive manufacturing, process comparison, design optimization, weight reduction

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1 INTRODUCTION

LIKE any other subset of engineering, manufacturing has advanced significantly over the years. The last four decades have seen invention of many new manufacturing methods, mainly due to widespread use of computer technology and automation. While conventional manufacturing methods have been subtractive in nature –i.e.: the process called for removal of material from the job, such as milling, grinding, etc. – a new approach has been developed over the last five decades: Additive Manufacturing (AM). If we were to think laterally for a moment - weld overlay, clay pottery or civil construction using mortar could be considered fundamentally additive in nature. But the term 'Additive Manufacturing' is reserved for a specific group of manufacturing techniques. AM, as the term implies, is the process of producing a part or an item by adding material, step by step. 3D model or Computer Aided Design (CAD) data is used to draw spatial information about the part. The part is then split into layers, and each layer is sequentially built one on top of another. The end product is the result of all the layers merged together to form a single entity. Many review papers have been published detailing the different processes which fall into the category of AM [1, 2]. There is also literature that focuses on specific advances in AM, such as Micro-Electro-Mechanical systems [3]. Some technologies that come under the purview of AM are:

1. Stereo-Lithography (SLA)
2. Selective Laser Sintering (SLS)
3. Fused Deposition Modelling (FDM)
4. Laminated Object Manufacture (LOM)
5. Solid Ground Curing (SGC)
6. Direct Metal Laser sintering (DMLS)
7. Selective Laser Melting (SLM)

1.1 Concurrent engineering

With Due to its speed, AM plays a significant role in Concurrent Engineering (CE), which is a relatively new approach to product design [4]. It has been widely adopted in recent years because of its advantages: faster execution and better end product. Sequential engineering, the traditional method for product design, is split into distinct steps. It is also known as "Over-the-Wall engineering". In sequential engineering, information flows from one step to the next, and only when all the information required for a particular phase, say manufacturing, is received, the tasks are commenced. However, concurrent engineering calls for an organic overlap between different phases of a product design lifecycle. There is a continuous flow of information between different teams such as design, marketing, production and QA. It also calls for parallel execution of tasks instead of sequential [5]. Departments work like a set of gears, where the rotation of one gear has an immediate effect on the preceding and succeeding gear, as shown in Fig 1. AM is primarily used to create and study prototypes to refine the design before production, but it has now made much headway into the production space.

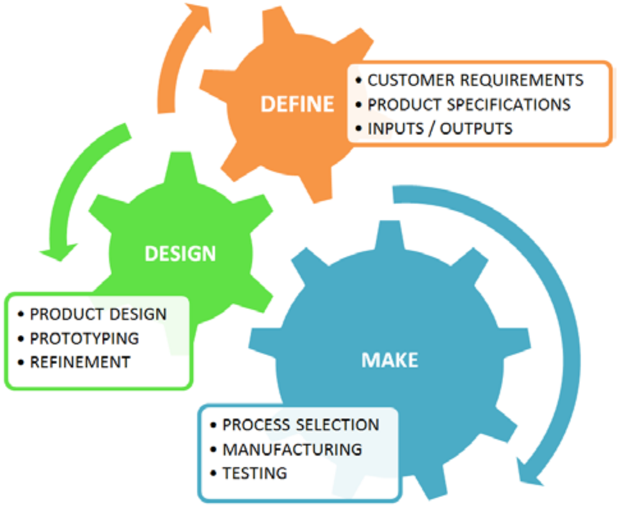

Figure 1: Concurrent Engineering Visualisation

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1.2 Rapid Prototyping and 3D printing

These terms are commonly used, but are often referenced incorrectly to describe other processes. Rapid prototyping (RP) is an activity which calls for manufacturing prototypes using CAD models, at a quick pace while the design process is still underway. RP is tied to the speed of manufacturing a demonstrative product, which closely simulates the final product, and not the manufacturing process itself. However, precision 3D printing machines, which are more accurate and can produce bigger parts, are referred to as Rapid Prototyping Machines. Machining processes are also used for RP, and every process has its own advantages and dis-advantages [6]. Although in reality, AM processes are widely selected for RP, it has become a widespread misconception that RP refers to AM itself. 3D printing originally referred to a specific type of AM process, which relied on inkjet printer heads. But today, it is broadly used as a synonym for AM. Although AM is still considered the correct technical term for this group of manufacturing processes.

1.3 Vacuum casting

Casting is a widely used manufacturing technique. It is cost effective for manufacturing large volumes of parts with complex shapes. Although casting does not come under the purview of AM, Vacuum casting and Investment casting are commonly used processes for RP [7, 8]. Vacuum casting is used for non-metallic parts, including rubber like materials, whereas Investment casting is used to make metal parts, particularly aluminium components. To provide additional insight on the RP aspect, Vacuum casting has been included in this paper.

2 OVERVIEW OF ADDITIVE MANUFACTURING PROCESSES

In order to compare different processes used to make the parts in focus and engineer designs to get the best result for these processes, a fundamental knowledge about the technology is necessary. Following is a brief explanation of the 4 methods that this paper focuses on:

2.1 Sterolithography (SLA)

In Stereolithography, a photosensitive polymer or resin is used that solidifies upon incidence of Ultraviolet light. SLA machines have a container of resin, as shown in Fig. 2. Inside the container is a platform which can move up or down in vertical direction. The part is traced out layer by layer onto the surface of the resin pool by a ultra-violet light source. The thin layer traced out solidifies due to chemical reaction. The platform then moves down by a fraction and the next layer is traced out on the resin surface. Each layer bonds with the one under it and the process continues till the entire part is completed [1, 9].

2.2 Selective Laser Sintering (SLS)

Selective Laser Sintering is similar to SLA. In this process, instead of a resin, the container is filled with build-material powder. A laser is used to melt a layer on the powder bed surface, which fuses upon cooling with the previous layer, building the part. When a layer is completed, the bed containing the powder moves down, and a roller deposits a fresh layer of powder [1, 9].

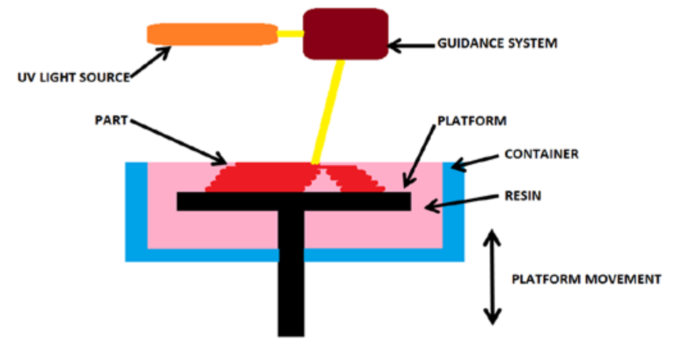


Figure 2: Stereolithography

2.3 Fused Deposition Modelling (FDM)

In Fused Deposition Modelling process, a movable nozzle deposits a stream of molten material onto a platform. The part is traced out layer by layer and the build material is heated to a point just above its melting temperature so that is solidifies quickly upon exiting the nozzle, and fuses onto the underlying layer. Cooling time is in tenths of a second [10]. This process is akin to an inkjet printer printing on a flat piece of paper. The difference is that in FDM, the head moves in all 3 axes, as the layers are built, and instead of extruding ink on paper, it extrudes build material in 3-dimensional workspace, as shown in Fig. 3.

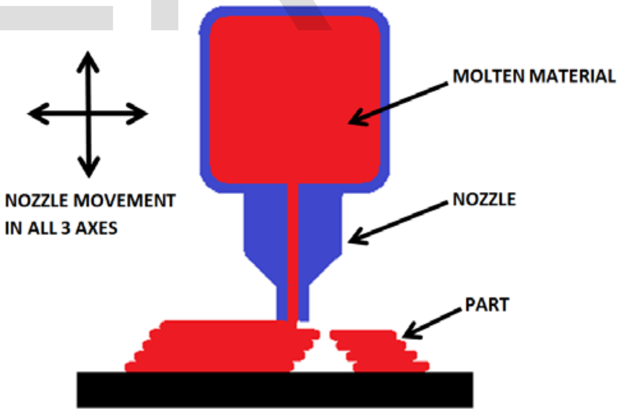


Figure 3: Fused Deposition Modelling

2.4 Vacuum Casting

In Vacuum Casting, a master of the part to be moulded is first created, often using Stereolithography. This master is then used to create a silicone-rubber mould. Even the most complex and intricate shapes can be made through this process, as the flexibility of silicone eliminates the constraints any typical moulding process would bring to the table. The mould is then used to cast part copies, under vacuum condition, as shown in Fig. 4. Vacuum ensures complete filling of the mould cavity and eliminates air bubbles. This mould can be used to create up to 20 parts, after which the dimensional accuracy is lost. Vacuum casting is one of the commonly used processes for RP.

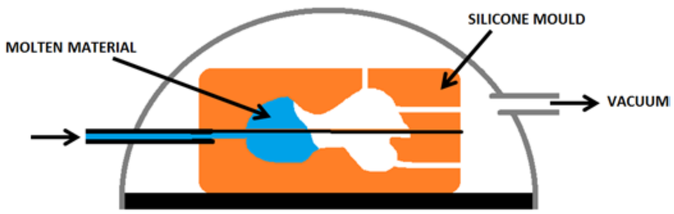


Figure 4: Vacuum Casting

3 PART ENGINEERING FOR ADDITIVE MANUFACTURING

3.1 Weight reduction

One of the biggest advantages of choosing additive manufacturing processes is that hollow portions/voids or honey comb/truss structures can be incorporated into a part, leading to significant weight reduction [11, 12, 13], as shown in Fig 5; features that would not be possible to create otherwise using conventional manufacturing processes. This advantage is unique to AM processes. This gives a significant benefit in terms of cost savings as well. For processes such as SLA or SLS, the part cost depends on the volume of material consumed. Thus, a part with lower total volume of material will cost less. However, while using such design features, the intentions must be clear – whether it is a temporary cost reduction measure or a permanent design feature.

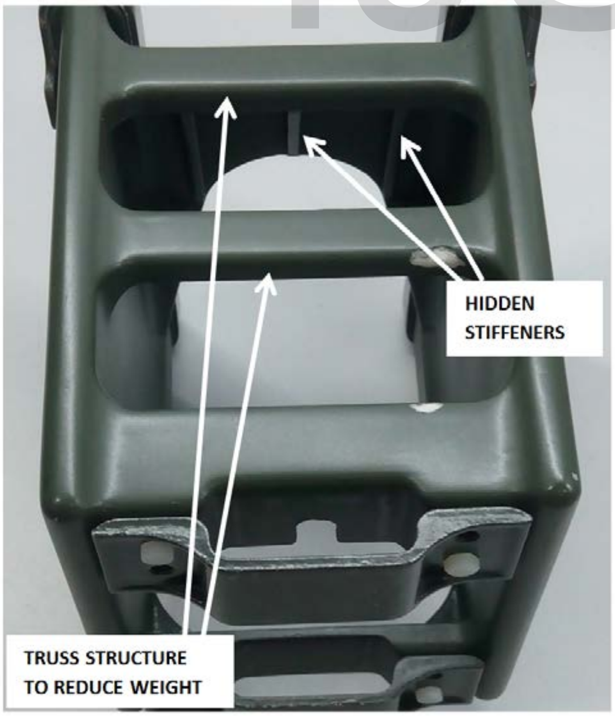


Figure 5: Weight reduction with truss structure (SLS part)

Certain features may not make it to the production variant of the design due to production process limitations, and this must be accounted for, e.g.: increase in weight, alternate manufacturing process selection, etc. Otherwise, the production process planning must be done accordingly to ensure these features are manufacture-able in the production stage.

3.2 Structural strength

Structural strength of parts and the transfer of load from one component to the other are critical design considerations. The AM processes discussed in this paper deal with polymers only. Most commonly used polymers in AM are at a disadvantage when demands of high strength need to be met that can only be achieved using metals. Although processes such as Direct Metal Laser Sintering (DMLS) [14, 15] can be used to build metal parts just as one would in SLS, it is not the most economical option. The question then is how to maximise the strength of parts made from these processes. Some examples are as follow:

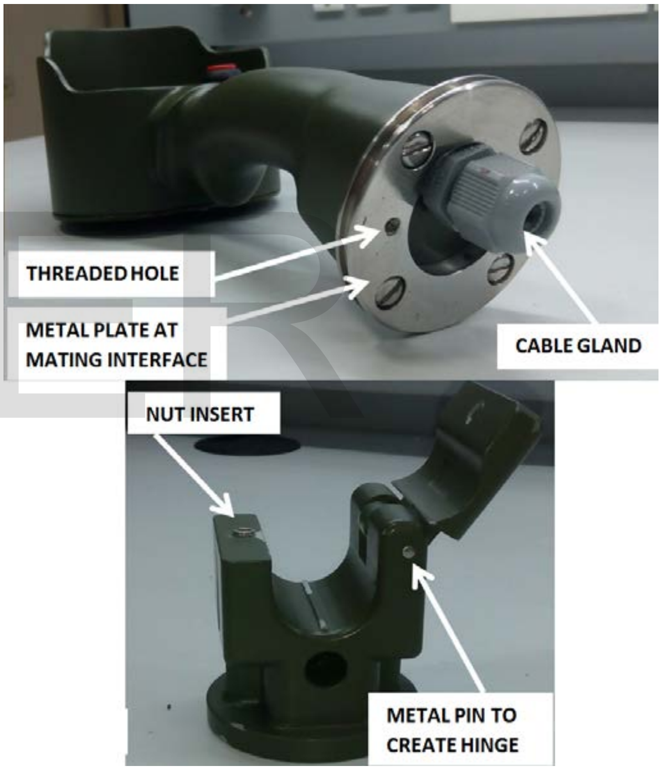


Figure 6: Metal inserts and interfaces to strengthen parts (SLS Part)

1. Use of inserts to strengthen features, such as nut inserts for threads as shown in Fig 6. Such inserts can be placed in the AM machine bed before manufacturing, and as a result, the part is built enclosing the insert within it seamlessly.
2. Press fitting metal rods in recesses inside the part to add additional strength. This press fitting can also be used to create hinged joints, as shown in Fig 6. Press fit tolerances can be achieved very easily with AM processes.

3. Embedding metal skeletons within the part and metal interfaces at areas that undergo severe wear and tear, such as threaded load bearing mating joints, as shown in Fig 6.
4. Parts made by processes such as FDM do not have isotropic strength properties. The shearing strength is low in the part-construction plane. Thus, the orientation of the part in the bed during manufacturing can be pre-meditated to achieve optimal part strength with respect to functionality. The shearing wear is shown in Fig 7.
5. Use of stiffeners and webbing to increase strength. Well placed stiffeners can counteract shearing and buckling under load for thin walls, as shown in Fig 8.

Figure 7: Shearing in weak areas along build plane (FDM part)

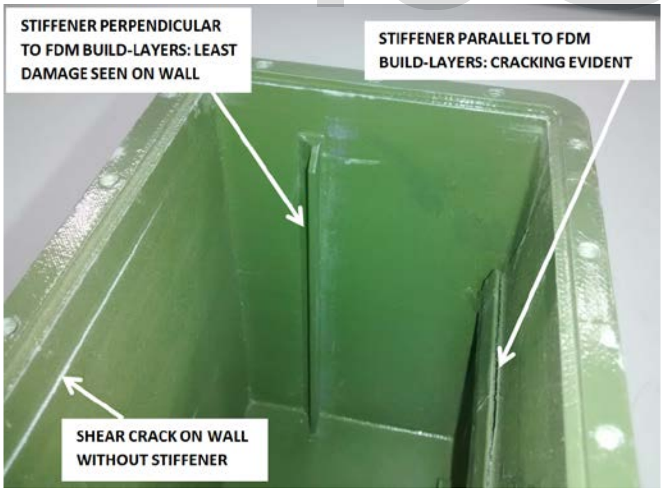


Figure 8: Stiffner placement (FDM part)

3.3 Use of Ultrasonic welding and Adhesives

One limitation of additive manufacturing processes is the maximum size of the part that can be made in the machines. Conventional manufacturing machines, such as CNC Vertical Milling Centers and Lathes, can be used to make large parts, as machines are available with very large beds, whereas contemporary AM machines cannot make parts of such large sizes because of the limitation in bed size. To overcome this, adhesives are widely used with additive manufacturing machines that have smaller bed sizes. The required part is split into smaller sub-parts, which are then manufactured though additive manufacturing process. Next, all the sub-parts are glued together, resulting in the required final part. It is important to note that such techniques are suitable predominantly for visual-prototypes rather than functional ones. Adhesives can be used in functional prototypes as long as their use does not affect the functionality of the assembly, primarily in terms of strength of the components. One major disadvantage is using stronger adhesives results in permanent joints which cannot be undone. For example, in case of a prototype casing for a battery, shown in Fig 6, initially adhesive was used to assemble the thin walled enclosure. When the battery was to be accessed post assembly, the case had to be cut open and as a result, was scrapped.

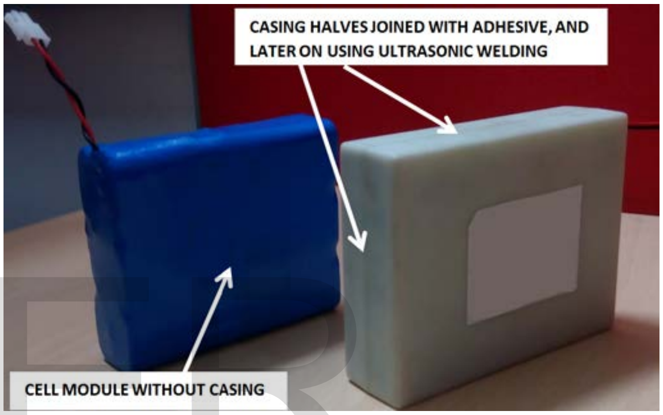


Figure 9: Battery case assembled (SLA Part)

Figure 10: Ultrasonic Welding machine used to join cases

Ultrasonic welding of thermoplastic materials [16, 17] is a method that can be well used for this requirement, as shown in Fig. 10. In ultrasonic welding, the components to be welded are vibrated at very high frequencies. The vibration results in collisions of the surfaces in contact, resulting in heat. This heat melts the material in the vicinity of the contact surfaces, which fuse to form a weld joint. Similar thermoplastics can be easily joined by this process. It is a simple and rapid process with very minimal tooling cost. But the drawback is that these parts must be suitable for the process. The advantage of this process is that it eliminates the need for adhesives and associated curing time.

3.4 Surface finish

In AM processes such as FDM, SLA and SLS, parts are built layer by layer. This results in characteristic surface textures on part surfaces, as shown in Fig 11.

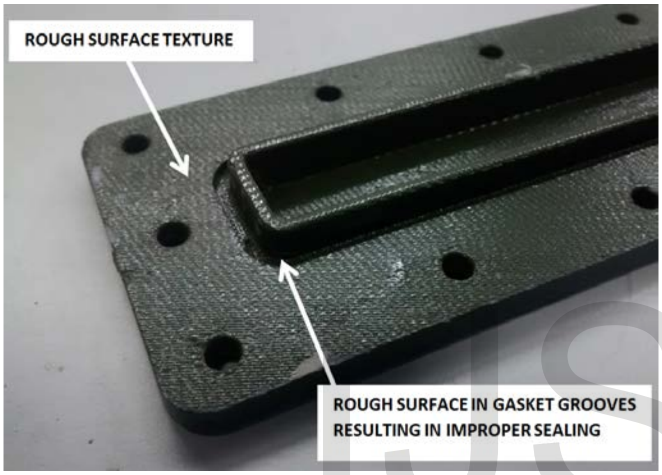


Figure 11: Rough surface on panel (FDM Part)

Figure 12: Rough surface on inner walls (SLS Part)

Most surfaces, which are easily accessible, can be polished to achieve a smooth finish, although the polishing may result in unwarranted deviation from the required dimensions. But some internal surfaces cannot be polished as they may be hard to reach and remain with a rough surface texture. This impacts critical mating junctions, like gasket sealing, as shown in Fig. 12. Thus, the best achievable surface finish across all the surfaces of a part needs to be considered when designing a part, as well as selecting the AM process. Especially when designing critical features such as grooves for seals, which require good surface finish throughout for proper sealing, special attention must be paid. The degree of surface roughness also depends on the machine. Advanced AM machines, which build parts with ever smaller layer thickness, give better results in terms of surface finish. It is always best to examine a part made from the machine intended to be used, so that the surface of the end-product surface can be better predicted.

3.5 Complex features & assembly manufacturing

Two of the distinguishing features of additive manufacturing processes, such as SLA and SLS, are that whole assemblies, with multiple mating parts, such as a chainmail structure [18], can be built at the same time and features such as 'U' axis hole and hollow voids can be made as well, as shown in Fig. 13. Multiple parts of an assembly can be manufactured using additive manufacturing simultaneously in their assembly-positions [19]. The result is a complete ready-to-use assembly, which can have moving parts as well. This can greatly reduce manufacturing time and, to a small extent, manufacturing cost. The mating parts are differentiated from each other because of small gaps that exist between them. These gaps are introduced during the manufacturing process to prevent them from forming a single continuous entity. Water resistant assemblies can also be made by providing grooves for seals at mating interfaces, and adding a rubber sealing ring later on. In using these features, the final manufacturing process must be kept in mind.

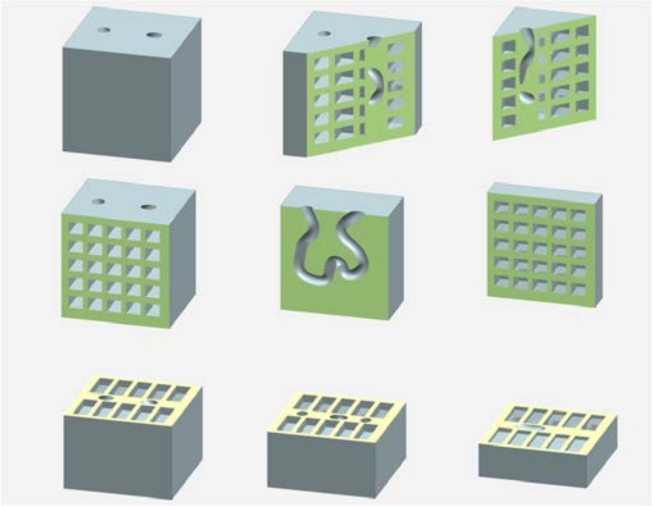
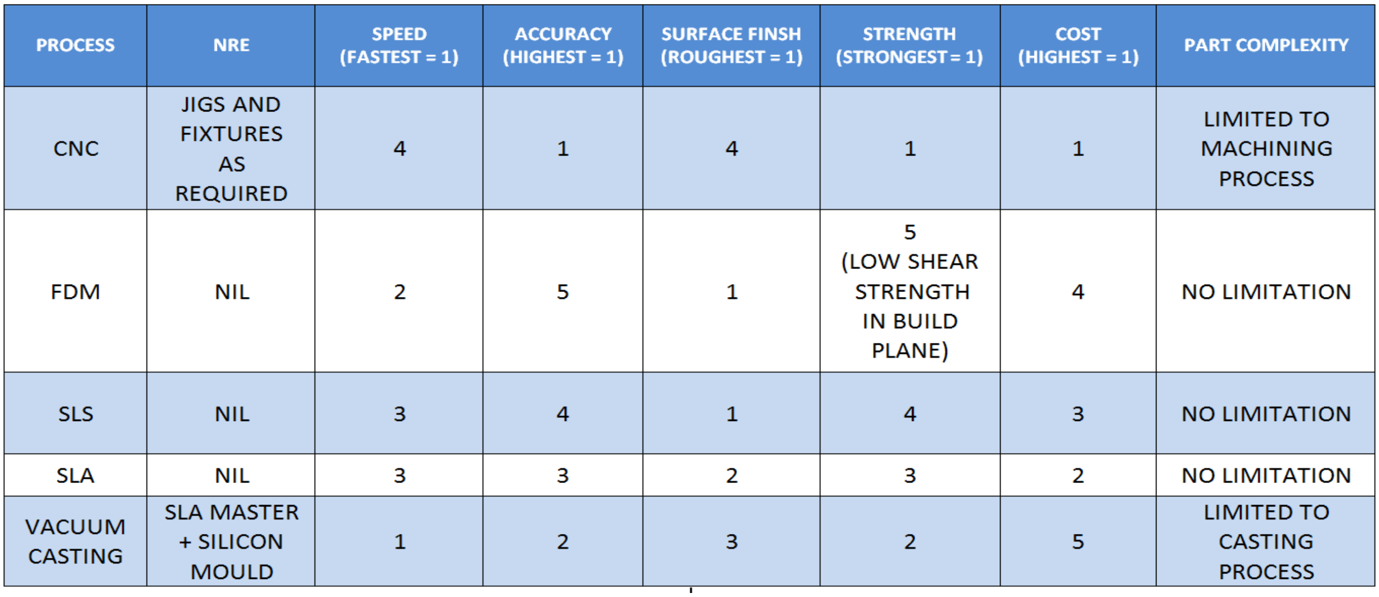


Figure 13: Sections of a part showcasing feature complexity



PROCESS	NRE	SPEED (FASTEST = 1)	ACCURACY (HIGHEST = 1)	SURFACE FINSH (ROUGHEST = 1)	STRENGTH (STRONGEST = 1)	COST (HIGHEST = 1)	PART COMPLEXITY
CNC	JIGS AND FIXTURES AS REQUIRED	4	1	4	1	1	LIMITED TO MACHINING PROCESS
FDM	NIL	2	5	1	5 (LOW SHEAR STRENGTH IN BUILD PLANE)	4	NO LIMITATION
SLS	NIL	3	4	1	4	3	NO LIMITATION
SLA	NIL	3	3	2	3	2	NO LIMITATION
VACUUM CASTING	SLA MASTER + SILICON MOULD	1	2	3	2	5	LIMITED TO CASTING PROCESS

Table 1: Comparision of Rapid Protoyping processes

4 COMPARISON OF AM PROCESSES

The exact comparison of different processes depends on the part which is used as a baseline for comparison and the quantity of parts made. In general, AM processes are cost effective for low-volumes. The ranking of processes considering a specific parameter, such as speed, cost or accuracy, may not be the same as it would be considering another parameter. Variations in comparative studies are to be expected [19] and need to be accepted with due respect to the baseline variation (part chosen, quantity manufactured, etc.). Table 1 details the relative standing of different RP processes, as observed in this study. Some of the parts have been shown in the preceding figures. Quantities manufactured varied from 10 to 15 numbers. It is to be noted that cost is a parameter in which the rankings are greatly affected by quantity. Another key factor to consider is the number of errors generated during model data conversion into manufacturing format [20], as this will greatly impact the accuracy of parts in different directions of the co-ordinate system.

5 CONCLUSION

As with any manufacturing activity, selecting the best manufacturing process and engineering a part to achieve optimum results are the two key steps to get desired output. The same is true for additive manufacturing. While prototype parts made using AM processes have inherent disadvantages, such as higher cost, lesser strength and limited size, they also have advantages such as faster completion times, no tooling requirements and the ability to take on complex shapes, which are not possible with conventional processes. Factors such as cost and end-part-requirement must be considered while selecting from the AM processes. And based on this selection, parts need to be designed suitably to achieve a better result, compared to staying with the original stock-design. Vendors who render AM services oblige requests for samples readily and can give first-hand knowledge about the processes. This can be of great help in selecting the right method. AM processes have already made their way into production lines, and are expected to spread rapidly [21]. GE recently demonstrated the capability of additive manufacturing by building a working jet engine through Selective Laser Melting (SLM). Processes like SLM and Direct Metal Laser Sintering (DMLS) result in parts made of metal, which are stronger and can be used in production. Therefore, today, it is essential that an engineer or a designer not only is familiar with this technology, but also knows how to optimise designs based on specific nuances of each process. As a result, he or she can make the best use of a RP exercise to enhance the final product significantly. Looking into the future, the level of complexity in parts that AM processes can achieve is simply astounding. The day when a part needs more than one machine to manufacture may well be nearing its end.

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