

Consideration of SLS advantages in
enablement of Lean and Agile NPD and
manufacturing activities for a micro entity
scale business

Selective Laser Sintering (SLS)

Agile and lean, from NPD to
product

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Introduction

The essay examines the potential impacts of adopting an agile approach to prototyping and later small-scale manufacturing, specifically focusing on an innovative SME developing new products in the healthcare industry.

The business has recently been evaluating emerging Industry 4.0 strategies to address the near-term requirements of new product development (NPD) which demands timely multiple small to medium size part prototyping. The prototype parts being produced are almost exclusively functional parts requiring mechanical strength and acceptable resistance to periodic exposure to certain sterilant chemicals in liquid and vapour phases.

As the NPD progresses, several functional prototypes are required for user evaluation trials and after the outcomes of the user trials, the project will naturally progress to small-scale manufacture of a small number of new healthcare product variants.

The business had adopted Knowledge-Based Maintenance (KBM) as a fundamental strategy in NPD and thereafter manufacture and deployed product support. Consideration of the family of alternative KBM strategies has led to the selection of the Prescriptive Maintenance (PM), (Matyas et al., 2017) approach to the NPD, manufacture and support of its future products.

To deliver a PM-based production and support model, attention must be focused on the need to adapt to data and intelligence feedback from deployed products to employ that feedback intelligence in potential iterative design variations. The PM approach allows continuous adaption of the product design during its service life to ensure a “low service intervention” longevity.

The PM approach necessitates an agile response in ongoing product manufacture pipelines where the need to adapt or modify a component to mitigate an anticipated in-service failure.

The business has also committed to societal benefit, reducing carbon footprint in NPD, manufacturing and product support, and minimising waste, in summary, a lean culture.

In light of the business aspirations, additive 3D manufacturing technologies have been considered (although the considerations are not fully detailed in this work) and a newly launched Selective Laser Sintering (SLS) workflow solution has been investigated before potential purchase and installation.

The Fuse1+ SLS (Formlabs, 2022a) promises to deliver prototyping capability, functional and structurally acceptable parts meeting both prototyping and manufacturing specifications, low cost of operation, low consumable waste and provide for a Just In Time approach to manufacturing and resultant minimal stock inventory.

Selective Laser Sintering (SLS)

SLS, an additive manufacturing (AM) technology, uses high-power laser energy to melt and fuse small spheres (typically 50µm diameter) of polymer material into a solid structure, based on a computer-aided design (CAD) generated 3D model. SLS printing has been an option for designers and manufacturers for some time, only recently has a low cost per part, higher productivity, and proven polymer powders and composite powders made the technology appropriate for a wider range of applications from rapid prototyping to small-scale and potentially viable custom manufacturing.

Advances in SLS workflow systems, materials, and CAD/CAM integrated software have made SLS printing accessible to a wider range of budget-constrained SME businesses, enabling small businesses to own these tools that were previously limited to ownership and operation by larger high-tech industries.

The business use case however has several specific requirements in the consideration of ownership, mechanical properties of manufactured parts, geometric accuracy manufacturing capacity, post-processing activity, energy costs and consumable costs, and waste minimisation.

SLS parts and influencing factors

Particle size and layer packing

Powders used as feed materials are normally specified to have the same size or size distribution and are typically spherical. The powder layer density characteristics are important for several reasons, minimising porosity can assist in ensuring a mechanically stable bed (layer) and a stable melt pool during the laser pulse exposures. However higher density leads to higher thermal transfer at exposure boundaries, potentially damaging neighbouring materials. A lower density layer (higher porosity) aids the cooling of the sintered material and facilitates the escape of gases released by the thermal stress of sintering. Lower density layers also insulate the boundaries of the sintered part from their neighbouring powder particles. Monodisperse spheres, spheres of uniform size (Averardi et al., 2020) aid in achieving higher density uniform packing of the powder monolayer, reducing porosity, and aiding thermal melt transfer.

A conflict, therefore, exists in the optimisation of layer density, but other factors beyond thermal transfer are affected including surface finish, part density, microstructure properties and mechanical properties affected by the porosity of the printed part (Delgado et al., 2012), (Lee et al. 2018).

Powder recovery

Polyamide 12 and polyamide 11 are commonly used polymers in AM manufacturing using SLS due to their conforming thermal properties. Depending on the efficiency of the model packing in the SLS build chamber, a large amount of powder material may be remaining following a building episode. The unsintered material is no longer considered “virgin” as it may have been within a Heat Affected Zone (HAZ) and subjected to thermal stress. The effect of HAZ is to deform and sometimes bind the micro spherical powders to their neighbours.

Polyamide 12 is a semicrystalline polymer which exhibits far superior strength and low warpage characteristics compared to those AM SLS parts manufactured using amorphous polymers (Dadbakhsh et al., 2017)

An important aspect of polyamide powder SLS is the percentage of post-build residual powder and how the waste can be recovered, reconstituted, and reused to produce structurally acceptable parts. Waste powder exhibits deteriorated molecular, morphological, mechanical, and thermal characteristics, rendering the waste powder unsuitable for direct use in the SLS process. As Polyamide 12 powder is an expensive commodity, there is an obvious economic direct cost in the resultant waste, but the waste also presents environmental costs as pollutants. Reuse or reclamation of waste powder presents an opportunity to 'lean' the manufacturing process and increase the parts manufactures per volume of input powder (Yang et. Al, 2020).

Particle shape, grossly modified in aged powders, impact the flow characteristics of the powder layer, affecting density, thermal transfer, and melt flowability (Averardi et al., 2020). Highly spherical particles can flow easily, rough irregular particles flow less easily. Melt Volume Rate (MVR), an index of flowability is an important measure for the SLS process. Virgin powders have a high MVR while aged powder a lower MVR (Ziegelmeier et al., 2014).

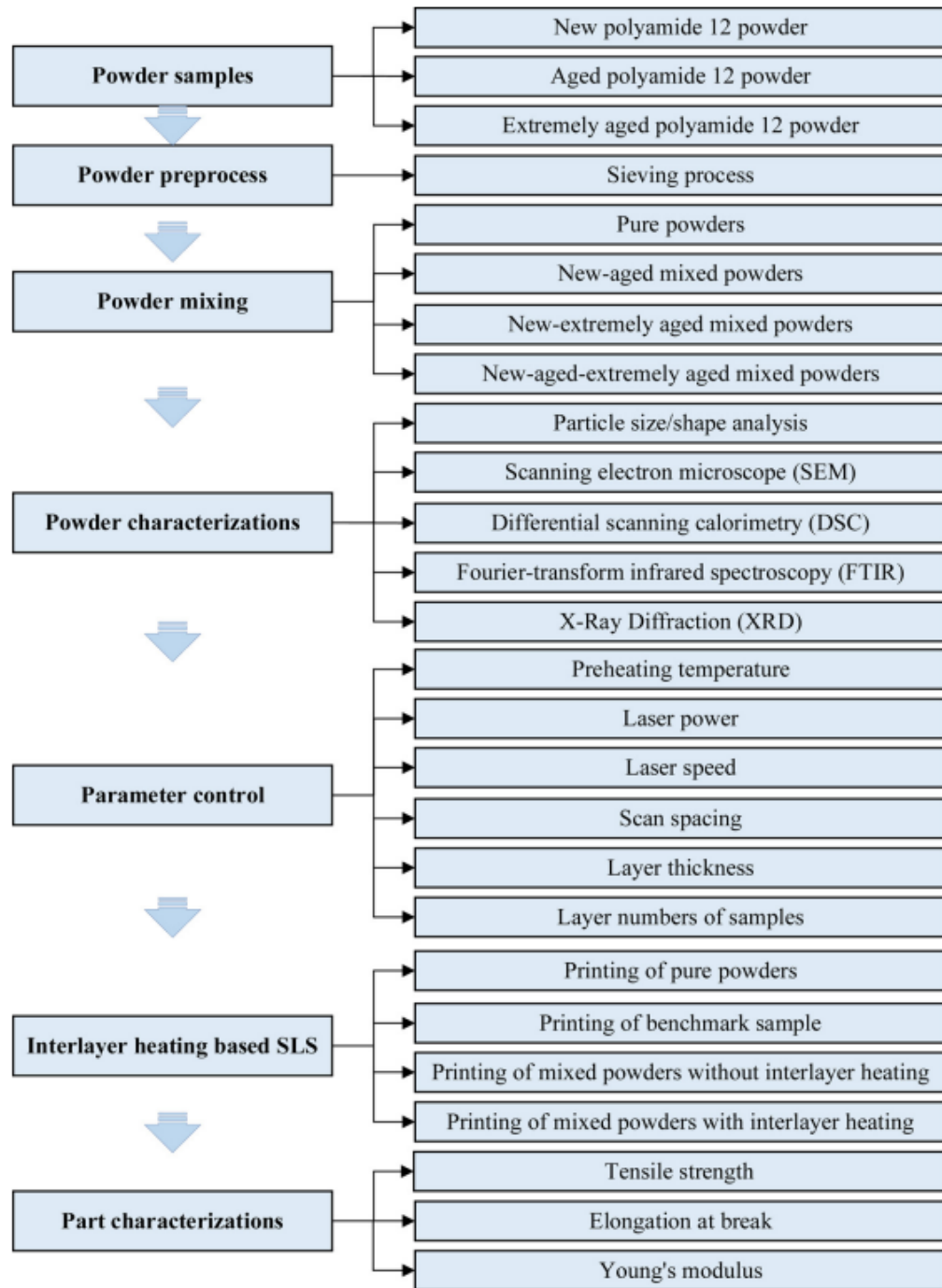


Fig. 1. Proposed method for reusing aged and extremely aged polyamide 12 powders.

A process control methodology (Fig. 1) to reuse the polyamide 12 powders of different ageing, different mixing percentages, and different compositions has been proposed (Yang et al., 2020). The methodology demonstrated reclaimed polyamide 12 powders can be consistently SLS manufactured into functional samples, with mechanical properties at least comparable to manufacturer expectations. The proposed methodology can generate printed samples with 18.04 % higher tensile strength and 55.29 % larger elongation at break using as much as 30 % of unprocessed extremely aged powders (Yang et al., 2022).

Geometric accuracy

In addition to structural characteristics, dimensional or geometric accuracy is of prime importance in SLS process manufacturing. An examination of material shrinkage and the Laser Heat Affected Zone (LHAZ) Fig. 2 was carried out to recommend adaptations and compensation to improve the parts' physical accuracy (Brajlih, et al., 2019).

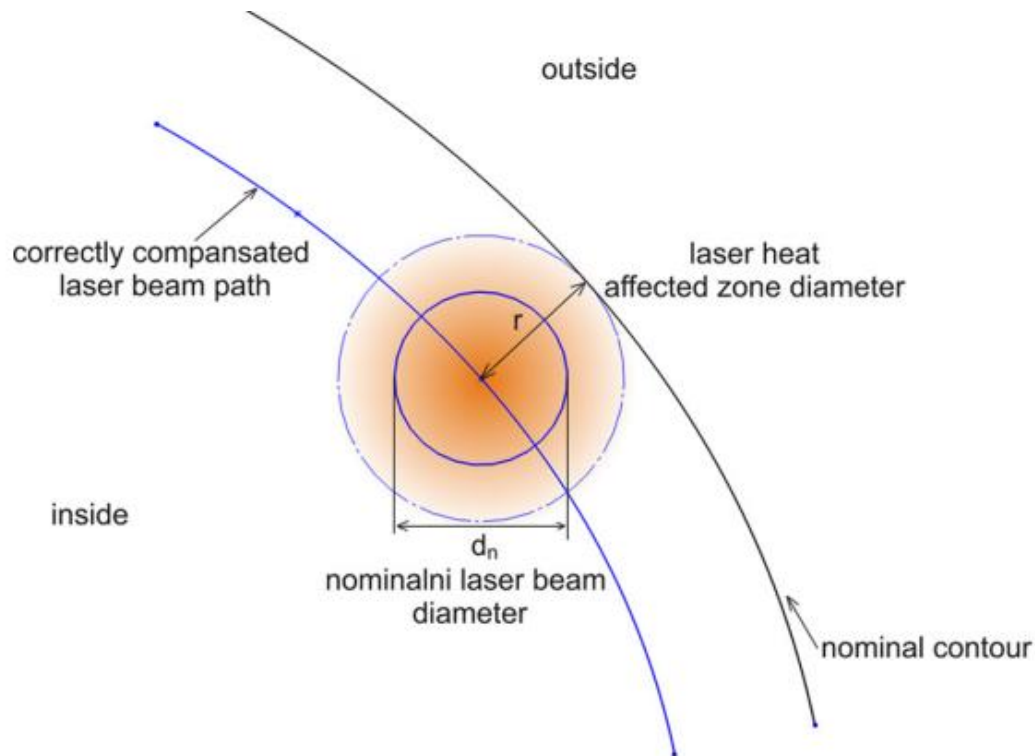


Fig. 2 From (Brajlih et al., 2019)

Only when actual shrinkages in all axes are compensated correctly and the laser path is offset for the actual radius of LHAZ, an accurate part can be produced by SLS (Brajlih et al., 2019) however the work does demonstrate that by careful consideration of the LHAZ induced shrinkage, optimally dimensioned parts can be manufactured.

Part placement in SLS build chamber does not significantly affect the part's accuracy but does affect the part's mechanical characteristics (Gazzerro et al., 2021). The placement is therefore a secondary but still important aspect of planning part stacking and placements with a build chamber, assigning parts with specified characteristics to appropriate locations within the build volume.

Use of anisotropy-enhancing fibres

SLS AM is now considered appropriate for the manufacturing of structural parts. Polymers with enhanced mechanical behaviours through the addition of strengthening fillers facilitate the printing of such structural parts. These fibre fill innovations and the flexibility of SLS manufacturing have greatly enlarged the application fields of AM components and the number of manufacturing solutions available in the market.

“components processed by selective laser sintering (SLS) or by fused deposition modelling (FDM) show properties, which depend on their building parameters. In SLS, the main parameters to be optimized are the laser power, the laser scanning speed and the distance between the scan lines. On

the other hand, in FDM technology, the extrusion temperature and the speed of filament deposition play a key role, in addition to the infill percentage and strategy, and the raster angle. In both these technologies, the parts produced can show different mechanical behaviours' depending on their orientation on the building platform, because this affects the placement of the layer interfaces." (Belhadi et al., 2018).

Enhancing the anisotropy of a built component is a potential advantage of fibre reinforcements, the enhanced characteristics include mechanical strength and thermal transfer (Mortazavian and Fatemi, 2015).

Fibre reinforcement of polymer matrices is a common method of increasing tensile and flexural strength and increasing resistance to localised fatigue-inducing stresses. Fibres are either continuous or short length i.e., chopped. Within the finished matrices, fibre can be aligned or non-aligned endowing significant different mechanical characteristics to the part. Fibres may be deliberately aligned by appropriate orientation within an AM build chamber in both FDM and SLS modellers, however in an injection moulded component there is no such control, and the fibres align according to thermal flow within the mould and can be considered randomly aligned.

One of the numbers of studies to examine the effects of fibre orientation within AM manufactured polymer matrices (Belhadi et al., 2018)., considered polyamide 6 with carbon fibre (CF) extruded by a Fused Deposition modelling technology in contrast with two commonly used polyamides, 11 and 12, with chopped CF fill. The CF diameters and lengths did differ somewhat between the three dissimilar matrix materials, the median fibre lengths being around 70um, and the nonorganic fill of the FDM material was significantly higher than that of the two SLS polyamide-filled powders.

Both FDM and SLS appeared to facilitate a significant aligning of the carbon fibres, the FDM alignment effect largely followed the extrusion laydown direction (FDM is built layer on layer hence the alignment effect is limited to a single plane within a build volume parallel to the build platform) The fibres in SLS powders appear to align relative to the spreader blade used to lay down a new Z layer of powder, again align effects are only apparent parallel to the bed and in the direction of the spreader blade movement.

The present business NPD includes parts which undergo repeated flexural stresses and are of a complex three-dimensional nature. Especially during the development phase, iterative prototyping cannot be economically realised by injection moulding processes, design and tooling costs are prohibitive and entail lengthy delays. The consideration of either FDM or SLS modelling methods with polyamides incorporating high fill rates of fibre additives present an opportunity to rapidly implement design iterations and efficiently manufacture the new components for empirical testing, quickly informing the follow-on design changes (if deemed necessary).

A lean approach

As business landscapes evolve and continue to change, the Lean Startup approach derived from the lean manufacturing approach has also evolved and now it is applied to each stage in both management and business, including the new products.

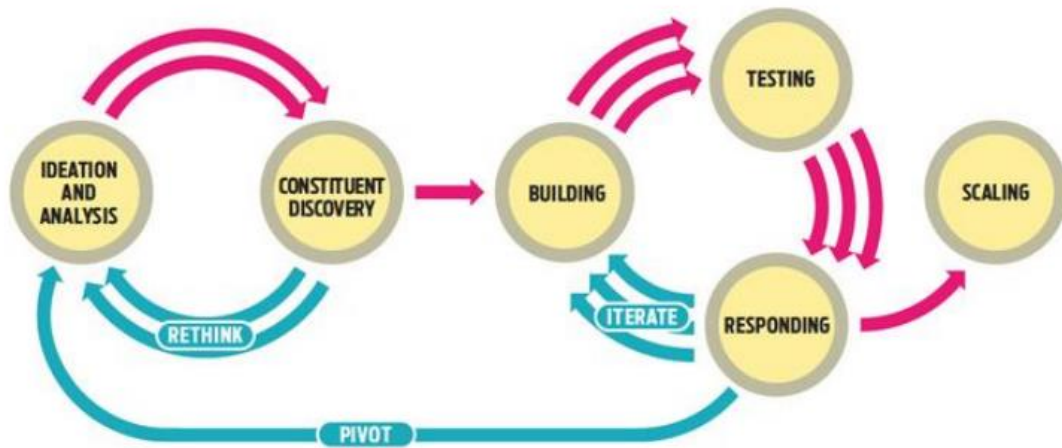


Fig. 3 Iteration Process in Lean Startup, from (Dewobroto and Marie, 2020)

It can be seen from Fig. 3, the capability to iterate in the generic workflow is important, and that capability is paramount to be applied to software, service and manufacturing areas in response to changes in the market space and to support the wider generic lean business model.

Shah and Ward (2007) defined lean production “as an integrated socio-technical system striving continuously to eradicate wastage by concurrently reducing or minimising supplier, customer and internal variability”. AM also provisions ‘lean’ in parts design and manufacturing costs. The cost of raw materials and the cost of transforming raw materials into parts or products is a key factor in business output pricing calculations.

Realising the business’ social responsibility has latterly become a focus to satisfy consumer and investor sponsorship. This requires the exploitation of processes with low impact on the environment, and energy-efficient and safe workplaces, which are economically viable. This requires not just making more sustainable products, but also environmentally friendly and produced in a socially responsible manner, but also the use of more sustainable methodologies to manufacture those products (Faulkner and Badurdeen 2014)

AM tools such as SLS and FDM potentially address the energy efficiency and a reduction in consumed raw materials per part output. Importantly viable minimum inventory related wastage, inventory deprecated as a consequence of a new improvement by design and potential response to either the top-down Prescriptive Maintenance design approach, a customer requirement or a market requirement.

AM tools such as SLS can be considered Reconfigurable Machine Tools (RMTs), capacity is an important criterion for the selection of an AM technology and its implementation as a production asset. SLS largely differ from SLA and FDM in several ways. SLS does not require support structures required by the alternative SLA and FDM, the supports are effectively sacrificial and cannot be recycled, and negatively impact lean policy. Energy efficiencies between the AM options are not considerable, arguably SLA requires the least energy in manufacture. Post-processing is an area

where substantial advantages can lie. FDM require support structures to be removed (if they were necessary due to part geometry as is often the case). SLA postprocessing involves both washing, removal of inactivated resin and a UV curing or hardening of the part. Isopropanol Alcohol (IPA) is commonly consumed in the process and constitutes an environmental hazard. Uncured resin washed from the part cannot be reused and therefore must be disposed of with an associated cost. The set up of resin baths and the postprocessing is a labour-intensive activity and should the overall objective of reducing manufacture to be lean and environmentally acceptable, collectively SLA processes appear not to be a prime candidate. For very low volume or prototyping, SLA is a solution worth consideration, however, it is worth noting parts are generally not structurally suitable for challenging environments. Post-processing FDM manufactured parts require manual removal of support structures and potentially hand refinishing. Support structures may be recycled but the economy of doing so is questionable. SLS requires minimal postprocessing, no support structures are necessary, and the optional recovery of unused powder forms the largest relative investment in labour. Due to the high cost of SLS powders the recovery process is desirable both in cost saving in reuse and reducing pollution should the waste be disposed of.

An agile approach

Edwards, (2022) states *“Some systems integrate prescriptive maintenance within a cyber-physical ecosystem, incorporating multidimensional data acquisition, AI-based data analysis, a data-driven and knowledge-based action recommendation engine, a cloud-based dashboard and integration with physical controllers as solutions.*

Over and above the benefits of Predictive Maintenance, prescriptive maintenance leverages custom built prescriptive algorithms to extrapolate several possible outcomes and rank those outcomes in an order defined at the time of development of the custom algorithms. This rank may be of cost to various value areas. It may be production volume, cost to operate or human injury or satisfaction. Knowledge based maintenance considers long-term effects of such policies and decisions on economic terms, as an integrated component of the production system, which effects value creations of the high-level commercial entity (Matyas et al., 2017).”

(Ansari et al, 2019) summarise the four preferred flavours of Knowledge Based Maintenance in eloquent and succinct paragraphs.

“Descriptive maintenance (Type I, Low Complexity, Low Maturity) answers the question ‘What happened?’ by providing information about previous maintenance operations. Thus, it supports information collection and analysis and increases the level of information visibility.

Diagnostic maintenance (Type II, Medium Complexity, Low Maturity) answers the question ‘Why did it happen?’ by analysing cause-effect relations, reasoning, and providing further technical details about former maintenance operations. Therefore, it supports knowledge generation and increases the level of knowledge transparency.

Predictive maintenance (Type III, High Complexity, Medium Maturity) answers the question ‘What will happen when?’ by learning from historical maintenance data, possibly in real-time, and predicting future events. Thus, it supports knowledge discovery and enhances the level of (semi-)supervised or unsupervised prognostic capabilities. Notably, this is often referred to as ‘Smart Maintenance’, ‘Data-Driven Maintenance’ and ‘Maintenance 4.0’, not only in scientific but also in commercial contexts.

Prescriptive maintenance (Type IV, High Complexity, High Maturity) answers the question ‘How can we control the occurrence of a specific event?’ (How should it happen?) by providing actionable

recommendations for decision-making and improving and/or optimising forthcoming maintenance processes. It also refers to the recent advances in enhancing self-organisation and self-direction capabilities of CPPS, which ideally aim at machine self-diagnosis and self-scheduled maintenance. Hence, prescriptive maintenance may reach the highest degree of maturity which involves complex methods to produce and reinforce adaptation and optimisation capability”.

Therefore, where does AM fit within the business’ aspiration toward an agile strategy?

Prescriptive Maintenance (PM) requires a means of responding to weakness or deficiency in deployed devices and/or support services. The capability of responding to necessary part redesigns by creating the required changed part in CAD and committing to manufacture by SLS or FDM. The revised CAD model can be further used in support of an evolving Digital Twin (DT).

A newer usage of the acronym AM refers to Agile Manufacturing, to differentiate it from Additive Manufacturing the present essay will use the acronym AMS to refer to Agile Manufacturing Systems. AMS allows a business several potential advantages, reducing production run lots sizes and rapid response to demand and product changes.

One aspect of AMS within a changing automated workflow is how the business manages the variations in the manufacturing process in assembly or production areas using digital work instructions. (Letmathe and Rößler, 2022) Workers using digitally animated interactive work instructions perform more efficiently in assembly tasks than those using traditional written or static assembly instructions.

Concurrent Engineering (CE) is also a methodology describing the concurrency of the approach to the integrated design of a product and related services, including manufacture and service support. Both CE and AMS perfectly complement the business’ agile strategy when coupled with SLS or FDM-based manufacture, in both the NPD stages and latterly discussed small-scale manufacture. The combination of Prescriptive Maintenance, AM and AMS provides a sound basis for a truly agile solution to both small and larger enterprises in adapting the holistic nature of an evolving market offering, that may be all of product, services, and support to its clients.

Functional prototyping

The present business use case requires a manufacturing technology which can address the generation of structural dimensionally accurate prototype parts with rapid iteration turnaround, and the capability to generate deployable robust parts for products in service. Agile manufacturing analysis of AM technologies teaches SLS as the most promising candidate.

Further to the prior consideration of fibre fill powders in SLS modellers, specifically how fibre orientation affects the anisotropic characteristics of the generated parts, additional methods of changing, preferably improving or adding new characteristics are considered.

Carbon black (CB) additives in polyamide 12 bulk powder processed by SLS cause novel anisotropic mutation (Espera et al., 2019). It was found bulk electrical resistivity decreased with CB percentages in small amounts, 1.5% to 3%, over which percentage the CB began to interfere with the sintering of the bulk polyamide layer. Up to 3%, CB appeared to block stress fractures from progressing thereby changing the sintered parts’ mechanical properties. Thermal conductivity changes of the CB /polyamide 12 parts also demonstrated desirable outcomes, improved thermal stability resulted in higher degradation temperatures than pure polyamide 12 parts. The addition of relatively small amounts of CB demonstrated the flexibility of additives in changing three important characteristics of the bulk powder, thermal conductivity/ stability, electrical conductivity, and mechanical strength/ resistance to impacts.

High-performance polymer (HPP) (polyether ether ketone, PEEK) blended with the common SLS bulk material polyamide 12 is further post-processed by novel heat treatment.

By two-stage heat treating the SLS PA12-PEEK component to eventually achieve a PEEK-only component (Chavez et al., 2022), effectively using the PA12 as a temporary matrix to support the high-temperature melt PEEK. The application is interesting as it points to additional flexibility of SLS beyond normal usage, but for the current business, the additional post-processing stages may prove to be too time-consuming to implement for a small number of parts, required with the enhanced anisotropic characteristics.

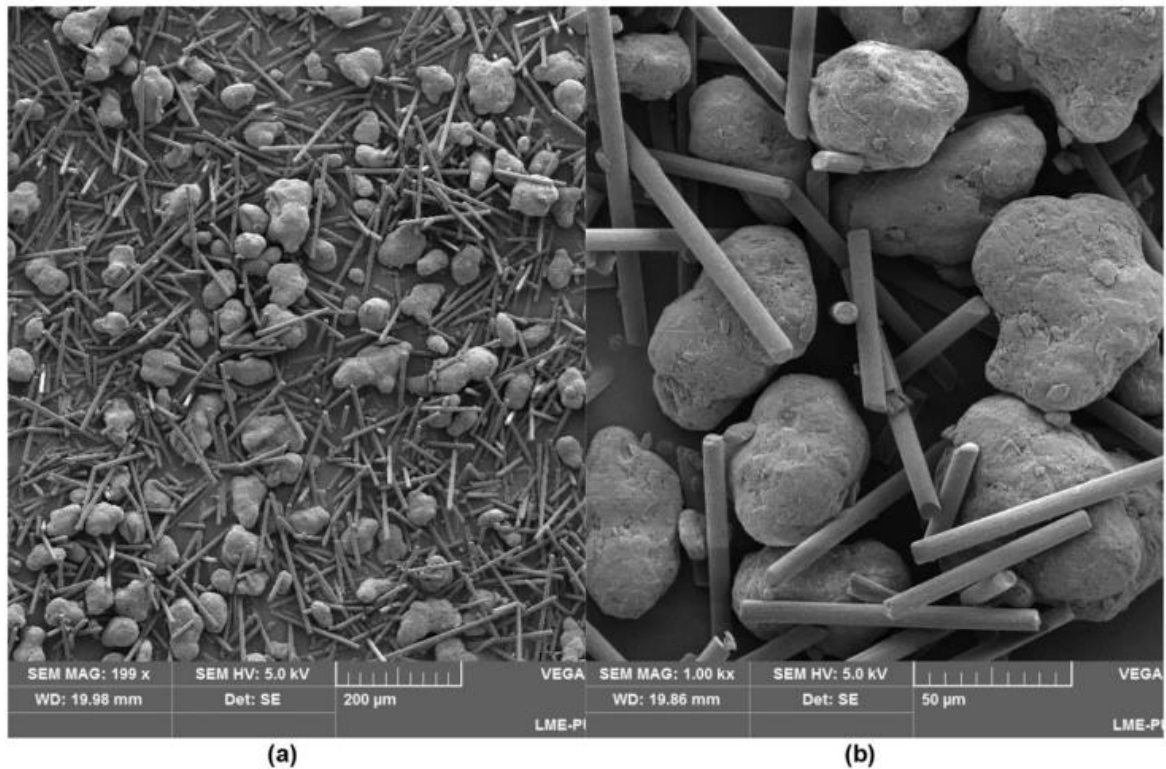


Fig.4 Electron Scanning Microscopy images of PA12-CF, from (Czelusniak and Amorim, 2020)

An in-depth investigation of the effect of laser sintering parameters on density, mechanical, and dimensional properties of carbon fibre–reinforced polyamide 12 (PA12-CF) components manufactured by (SLS) (Czelusniak and Amorim, 2020) demonstrated differing functional enhancements achievable by varying the configuration of laser line scan speed, line scan spacing and laser power, presented in Fig. 5, as relative relevance to several SLS generated part functional characteristics, namely density, elastic modulus, tensile strength and relative strain at break. What is of interest is the potential for the operational parameters of the SLS may be manipulated to bring about a preferred range of physical properties in a PA12-CF composite manufactured component, potentially optimising a part build beyond the base characteristics of a component generated using the standard SLS operational setting for the specific bulk powder. This flexibility adds to the ‘agile’ property of SLS as both a prototyping and small-scale manufacturing plant.

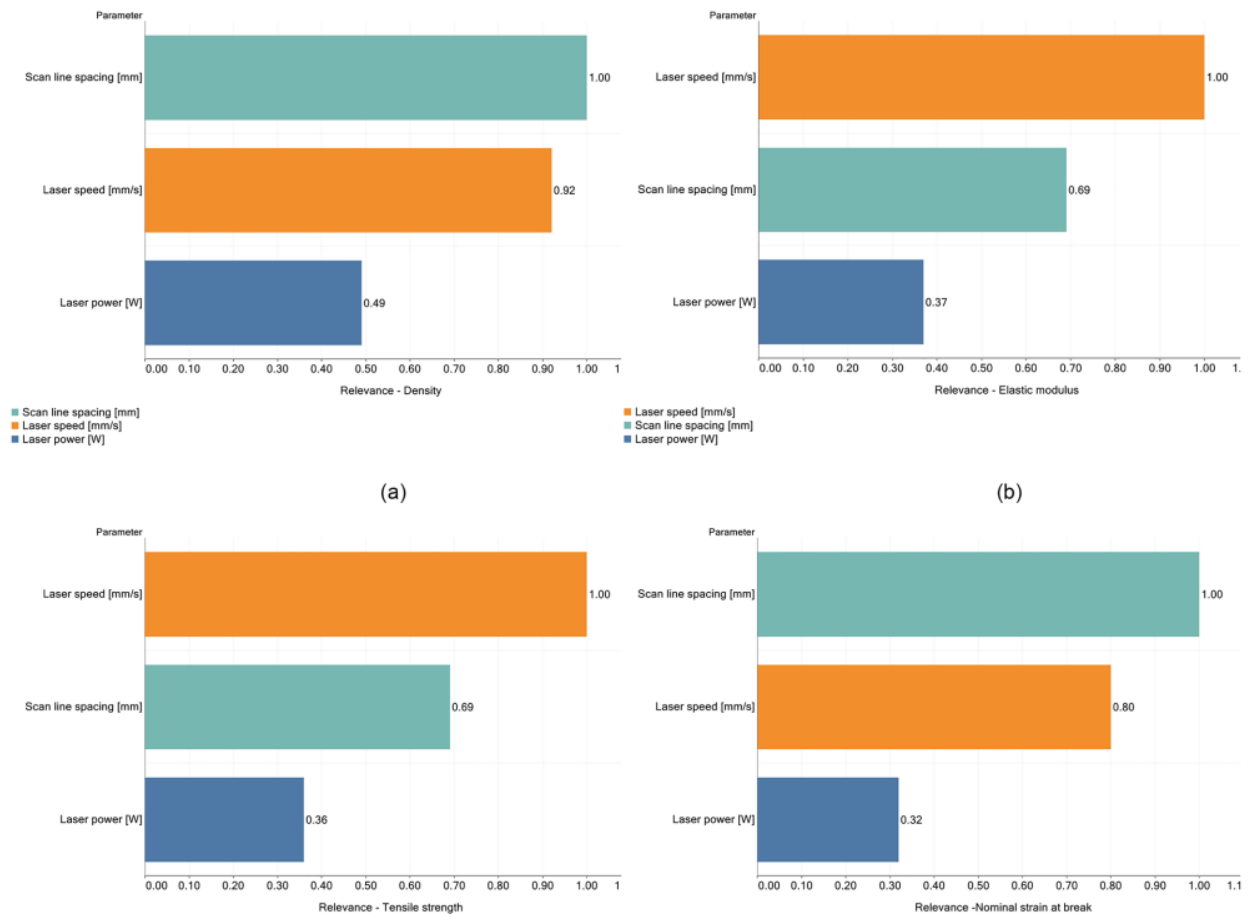


Fig. 5 Relative effects of SLS settings on physical characteristics of SLS parts, from (Czelusniak and Amorim, 2020)

Conclusion

A detailed consideration of the advantages and weaknesses of adopting SLS as a preferred part manufacturing technology has been presented. In particular and in light of the pseudo case study for the present business, engaged innovation and NPD with a view to small-scale manufacturing in the mid-term.

SLS production meets the requirements for rapid inhouse iterative prototype and testing without compromise in the accuracy of part geometry and functional structural characteristics by a selection of appropriate anisotropic modifying additives, such as carbon fibre, carbon nanotubes, carbon black powder and glass fibre.

The flexibility of SLS in common with alternative AM technologies supports the Agile development and manufacture methodology through to service and support delivery, coupled with the underlying design principles of Prescriptive Maintenance, cloud-based Artificial Intelligence and Machine Learning feedback and feedforward, collectively creating value in manpower-constrained SME.

Lean NPD and Continuous Engineering are also supported through the configurable, rapid (relative to other AM processes) manufacture of parts for development evaluation or bulk production at a small scale to meet a Just In Time assembly process, reducing waste by minimising stock quantities and bring the deprecated part stock to near zero. Production miles are reduced, as a single bulk powder delivery is more efficient than multiple manufactured part delivery miles, as would be the case of procurement by outsourcing to AM bureau services which would also entail lengthy lead times.

Environmental impacts of manufacture beyond 'miles' are minimised, the energy consumption of a small built chamber volume SLS is relatively low, and internal decisions can be made as to running builds which are not deemed to be filled to optimal capacity or may generate a higher amount of waste powder. Recovery strategies for maximal reuse of unsintered powders, the effects on the structural characteristics of the built components built from recovered powders, and the possible limitations of those 'recovered' parts have been considered and will collectively result in achieving a near zero consumable powder outcome.

Not least, intellectual property is retained in-house, and manufacturing know-how is ultimately preserved by the business's operation of its own SLS systems.

In closing, the present analysis has evidenced that investment in one of the latest generations of SME affordable SLS workflow solutions, such as the FormLabs FUSE1 + (Formlabs, 2022a) companioned by the SIFT post-processing station (Formlabs, 2022b) can have a significant impact in NPD, CE and small-scale manufacturing of functional parts. The exemplar workflow solution can also positively enhance the Agile and Lean credentials of the business in the support of a Prescriptive Maintenance driven bottom-up product and service design and market delivery.

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