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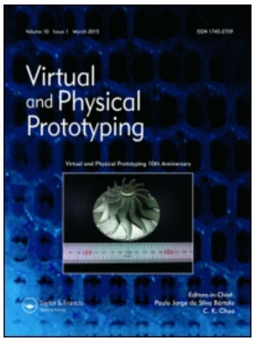

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REVIEW

A review on composite materials and process parameters optimisation for the fused deposition modelling process

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ABSTRACT
Fused deposition modelling is the most significant technique in additive manufacturing (AM) that refers to the process where successive layers of material are deposited in a computer-controlled environment to create a three-dimensional object. The main limitations of using fused deposition modelling (FDM) process in the industrial applications are the narrow range of available materials and parts fabricated by FDM are used only as demonstration or conceptual parts rather than as functional parts. Recently, researchers have studied many ways in order to increase the range of materials available for the FDM process which resulted in the increase in the scope of FDM in various manufacturing sectors. Most of the research are focussed on the composite materials such as metal matrix composites, ceramic composites, natural fibre-reinforced composites and polymer matrix composites. This article intends to review the research carried out so far in developing samples using different composite materials and optimising their process parameters for FDM in order to improve different mechanical properties and other desired properties of the FDM components.

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Additive manufacturing; fused deposition modelling; composite materials; optimisation; mechanical properties

Nomenclature

AM	additive manufacturing
FDM	fused deposition modelling
SLA	stereo lithography
SLS	selective laser sintering
IJM	ink jet modelling
SLM	selective laser melting
3D	three-dimensional
CAD	computer-aided design
ABS	acrylonitrile–butadiene styrene
PLA	polylactic acid
R&D	Research and Development
PA	polyamide
PC	polycarbonate
PMMA	polymethyl methyl acrylate
PE	polyethylene
PP	polypropylene
PMC	polymer matrix composites
SMF	simulated body fluid
PCL	polycaprolactone
PEEK	polyether ether ketone
FRP	fibre-reinforced plastics
CFRP	carbon fibre-reinforced plastics
TPE	thermo plastic elastomer
UTS	ultimate tensile strength
TLCP	thermotropic liquid crystalline polymers
ANOVA	analysis of variance
S/N	signal to noise ratio
COP	cyclo-olefin polymer
RF	radio frequency
MFI	Melt Flow Index
IC	investment casting
RSM	response surface methodology
TPS	thermo plastic starch
TCP	tri-calcium phosphate
SEM	scanning electron microscope
LCM	lithography-based ceramic manufacturing
MWCNTs	multi-walled carbon nanotubes
LDM	liquid deposition modelling
DSC	differential scanning calorimetry
OPEFB	oil palm empty fruit bunch
NMT	natural fibre mat-reinforced thermoplastic
GMT	glass fibre mat-reinforced thermoplastic
MRI	magnetic resonance imaging
CM	compression moulded
GF-ABS	glass fibre-reinforced abs use this style for level one headings

Introduction

In recent years, additive manufacturing (AM) technology has evolved rapidly and gradually shifted the focus from traditional application methods. Three-dimensional (3D) printing is used in various manufacturing sectors such as aerospace, automobile to bio-engineering. AM process offers the advantage in producing parts having complex shapes with shorter production time and reduced costs as compared to traditional manufacturing process.

AM technology is extensively used in engineering applications for customised products, functional and prototype models. Currently, many AM systems are accessible in the market such as FDM, stereo lithography (SLA), selective laser sintering (SLS), ink jet modelling and

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selective laser melting. These systems vary in terms of maximum space required, cost, building layers and type of materials used. When first introduced in the mid-1980s, in the form of SLA, rapid prototyped parts produced had showed significantly inferior mechanical properties when compared with parts made using other traditional manufacturing methods.

The FDM process was developed in the 1980s and was commercialised by Stratasys Inc., USA, in the early 1990s. FDM is being widely used in AM technology recently in producing various products across various manufacturing sectors because of its reliability, cost-effectiveness in producing 3D objects with good resolution, dimensional stability (Harun *et al*. 2009), wide material customisation (Plymill *et al*. 2016), simple fabrication process (Masood and Song 2004) and its ability to fabricate complicated geometrical parts safely in a favourable environment. FDM technology is very flexible and can be easily integrated with computer-aided design (CAD) software packages. Being a thermally controlled process, thermoplastic filament should be melted before the deposition process and hence caused limitations regarding the materials that can be processed using this technique. Only a few materials such as acrylonitrile–butadiene styrene (ABS) and polylactic acid (PLA) possess the right thermal (melting point, glass transition temperature, etc.) and rheological (Melt Flow Index (MFI) etc.) properties that can be easily processed using this technology.

As shown in Figure 1, there are two materials in the form of filament, namely support material and build material, which are rounded to a roll. The diameters of the filaments that are mostly used in the market are of 1.75 and 3 mm. The material should first be melted in a liquifier/extrusion head and then carefully deposited through a nozzle attached to the bottom of the head. The cross-sectional geometry of the part is traced using CAD modelling to fabricate three-dimensional parts in a layer-by-layer manner. The liquefier head operates along *X* and *Y* axes, whereas the build platform operates in the *Z*-axis.

FDM is the most commonly used in producing conceptual models, prototypes and engineering components. The characteristics of the final product such as strength, surface finish and porosity are extremely dependent on the process parameters of the FDM process.

Most of the researchers had concentrated mostly on the optimisation of the process parameters and were curious in studying the inter-relationship between different process parameters and their effects on the final product. Most research done recently includes the parameters such as layer thickness (Lee *et al*. 2005, Wu *et al*. 2015, Tian *et al*. 2016), diameter of nozzle, temperature of envelope (Sun *et al*. 2008), temperature of extrusion (Garg and Singh 2016, Boparai *et al*. 2016a), extrusion velocity, filler particle size, raster orientation (Es-Said *et al*. 2000, Lee and Huang 2013, Hill and Haghi 2014, Garg *et al*. 2016), filling velocity (Ning *et al*. 2016), raster angle (Chockalingam *et al*. 2016), road width (Anitha *et al*. 2001, Duigou *et al*. 2016) and raster gap (Mohamed *et al*. 2016). All these parameters should be controlled to optimise the FDM process for achieving best characteristics such as good quality, dimensional accuracy, less porosity, better mechanical properties and reduced deformation in the final product.

This paper presents a compendious review on development and optimisation of different composite materials used in the FDM system for improving the mechanical properties (tensile strength, fatigue, etc.) and identifies the areas where future Research and Development (R&D) work should concentrate for making this technology better and produce products with higher strength and other desired properties.

Materials used in FDM

Current FDM technologies available commercially possess some limitations on the use of a variety of the materials that can be easily processed using this technology. The heating element/chamber of the commercially available FDM machine has a maximum operating temperature of around 300°C, which indicates that high melting point materials cannot be processed using this technology (Bala *et al*. 2016). With this limitation, only thermoplastic polymers and some materials of low melting point are found to be most suitable materials for this technology. However, with increasing competition in the world economy, manufacturing industries face a challenge of manufacturing the products more expeditiously with reduced cost and without compromising on the product quality to meet the requirements/aspirations of the consumer and achieve competitive advantage (Mohamed *et al*. 2014).

As FDM is widely accepted as one of the promising technologies among industrial sectors in order to sustain the competition as it reduces development time and cost of the product which is the need of the hour, research is done in order to increase the variety of materials that can be processed using this technology.

Polymers

Currently, polymers are treated as most suitable for the FDM process due to their melting temperature which are in the range of commercially available machine and

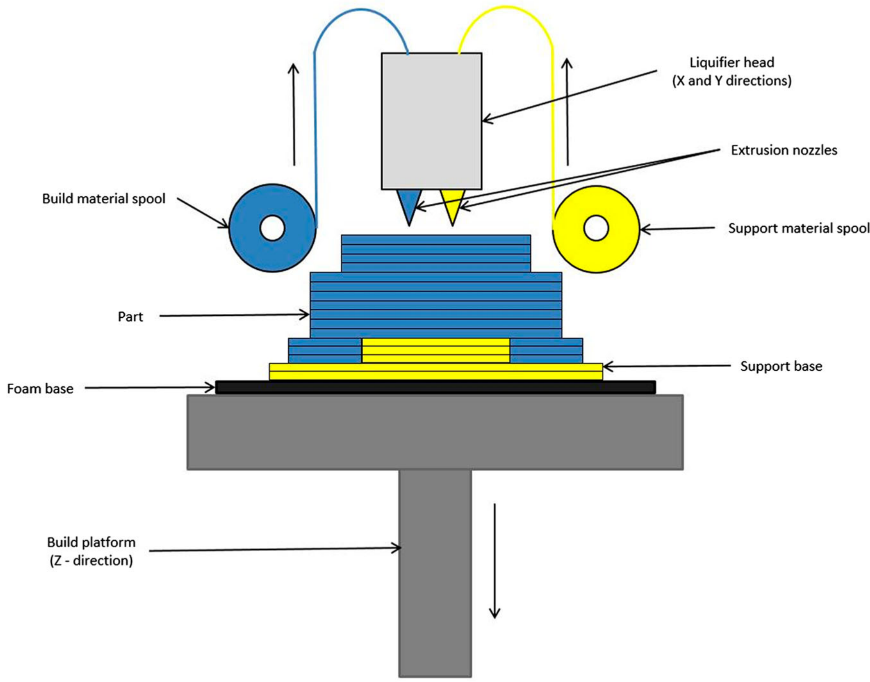

Figure 1. Principle of FDM.

they also provide sufficient strength to the final parts that can be utilised for wide-ranging applications (Bala *et al*. 2016). Thermoplastic polymers are mostly used in FDM, and ABS and PLA are the most popular. Some frequently used polymer materials in the FDM process include ABS, PLA, polyamide or nylon (PA), polycarbonate (PC), polymethyl methylacrylate (PMMA), polyethylene (PE) and polypropylene (PP). Some research is also done using a combination of the polymer materials such as ABS and PC, PLA and PC, PE and PP.

Polymer matrix composites (PMC)

In PMC, polymers are used as base matrix materials, and metals mostly in powder form are used as reinforcement which results in a material having particular properties from both materials. There is a rapid development of PMC in recent years due to the need for more advanced engineering materials with high strength and low weight (Iwai *et al*. 2000, Barekar *et al*. 2009). Properties such as adhesiveness, flexibility, conductivity, process ability, toughness and strength depend on the composition of the matrix and reinforcement materials (Bala *et al*. 2016). There are limitations regarding the composition of metal powder in PMC due to its effect on viscosity, but however its composition can be improved by using additives such as surfactants and plasticisers (Postiglione *et al*. 2015). Most commonly used metal powders for PMC are aluminium and iron powders with matrix materials such as ABS, PP and PA. The thermal property of the PMC increases with the increase in the size of the reinforcement/filler particle size.

Polymer ceramic composites (biocomposites)

Ceramics are very useful in bio-medical applications which require materials that are biocompatible, highly corrosion resistant and flexible (Ahlhelm *et al*. 2015). The most preferred materials for bone graft application are bioceramics, but are restricted to use due to their brittleness and poor mechanical strength; however, they can be used in the form of polymer ceramic composites which reduces their limiting properties (Kalita *et al*. 2003). Ceramics such as TiO_2, ZrO_2, Al_2O_3 and calcium ceramics are mostly used as reinforcement materials with polymer matrices such as polyamide (PA), polypropylene (PP) and PLA.

Bio-composites have brought significant advancements in the field of bio-medical and modern health-care sector and helped in the development of artificial human organs and tissue engineering (Kalita *et al*. 2003). Bio-composites/materials are those substances that are highly compatible with the simulated body fluid which resembles close to that of human blood plasma. Some of the biomaterials that are used in FDM are polycapro lactone (PCL), polyether ether ketone (PEEK) and PMMA.

Nanocomposites

Poor properties shown by FDM products can be improved by enhancing construction using raw materials such as adding nanoparticles that improve both mechanical and thermal properties (Bala *et al*. 2016). Addition of nanofillers increases the brittleness of the composite material due to the lack of adhesiveness and interaction between nanofillers and polymer material (Shofner *et al*. 2003). Adding nanomaterials such as carbon nanotubes, nanoceramic particles and metal nanoparticles to matrices such as polymers and metals has been used in the previous research and provided remarkable improvements in the properties of the final part (Haq *et al*. 2014, Tsiakatouras *et al*. 2014). The composition of nanoparticles by weight in a composite is optimised with the help of MFI, viscosity, etc.

Fibre-reinforced composites

There are different kinds of fibre-reinforced plastics (FRP) such as glass and carbon fibre-reinforced plastics (CFRP) which provide high strength and low weight to the product (Ochi 2015). At present, these FRPs are widely used in manufacturing industries particularly in the transportation sector such as aerospace and automobile sectors for replacing the components that are previously made of metal to reduce the weight of the component which increases the efficiency and performance of the vehicle. Use of FRP's as a raw material increases the application of FDM technology in industries. CFRP's possess superior properties such as wear resistance, corrosion resistance, light weight structures, high strength-to-weight ratio and high-dimensional stability. However, these FRPs are non-biodegradable which impacts the environment and their recycling after disposal is a global concern (Ochi 2015).

Recently, extensive research is being carried out for finding a replacement for FRP's due to the increasing environmental consciousness globally. Natural fibres are found to potentially replace due to the advantages such as low cost, low abrasive wear, low density, ease of availability, environmental-friendly and biodegradable nature. There are many naturally available fibres such as wood, bamboo, flax, coir, jute, sisal, vegetable fibres and oil palm. Natural fibres are abundantly available in the subcontinent, China and southeastern countries which are having the fastest growing economies in the world. Mostly, these fibres are used for conventional purposes in developing countries and hence there is a pressing need to find advanced application areas (such as FDM) to further strengthen their economies and can possibly become the manufacturing hub for natural fibre products.

Existing research on FDM materials

In the current scenario, dependence of various manufacturing/industrial products depends mainly on the polymer, plastics and composites due to their low cost, light weight and high strength-to-weight ratio (Singh *et al*. 2016a). Different types of composites on which extensive research is done have been discussed. Most of the research on the FDM materials has been concentrated on the suitability of the material, optimising the process parameters, rheological and mechanical properties, finding applicability in new areas such as tissue engineering and dimensional accuracy. Many researchers have suggested different composite materials that can be used in FDM with the help of the materials and tried to optimise the suitability of the material. Research on different kinds of composite materials is reviewed in detail.

Polymers

The effect of raster direction and layer thickness on the mechanical properties of 3D-printed PEEK has been investigated. The study revealed that both the parameters have a significant effect on the mechanical properties such as tensile, compressive and three-point bending strength. Through the experiments, the best results are obtained with a layer thickness of 300 μm and a raster direction of 0°/90°. The properties of 3D-printed PEEK parts decreased when compared to raw material, but increased when compared to 3D-printed ABS parts (Wu *et al*. 2015).

Cruz *et al*. (2015) conducted tensile strength measurements of 3D-printed samples at cryogenic temperatures of nylon which are used in both FDM (two samples) and SLS (five samples). The tensile strength of all the samples tested at 77 K increased except FDM nylon – 12 samples which showed a reduction in both *XY* and *Z* directions. All 3D-printed samples of SLS and FDM have an increased modulus at 77 K and are generally greater in the *XY* direction compared to the *Z* direction.

Perez *et al*. (2014) investigated the effect of addition of reinforcing materials on mechanical properties of the ABS base matrix. Four different combinations namely pure ABS, ABS and jute fibre, ABS and TiO_2, ABS with thermo plastic elastomer (TPE) were studied and compared. The work revealed that ABS/TiO_2 samples displayed an increase in ultimate tensile strength (UTS) when compared to commercially available ABS, whereas ABS/jute fibre and ABS/TPE showed a reduction in UTS. The study revealed that the ABS/TiO_2 sample exhibited brittle characteristics, ABS/TPE improved surface finish and ABS/jute fibre revealed highest roughness.

Gray *et al*. (1998) studied the feasibility of using thermotropic liquid crystalline polymers (TLCP)-reinforced thermoplastics in FDM. The experiment revealed the tensile strength of vectra A (TLCP)/PP mixed in a ratio of 40/60 in weight percentage has shown an increase of 100% and 150% when compared to ABS and pure PP, respectively. The tensile strength of plaques having 20% wt of vectra A is independent of processing temperature, whereas 40% wt showed a reduction when processed at a temperature exceeding the melting point of the reinforcement material. Lay-down pattern has a marked effect on the properties of the final part due to the anisotropy present in the TLCPs.

The fatigue analysis of ABS materials of different composition was performed. The study revealed that the printed ABS plus-P430 (production grade thermoplastic) material has a higher tensile strength but lower strain energy compared to printed ABS-P400 (general purpose) material. The print direction does not affect the fatigue degradation mechanism in the P430 material as parallel fatigue degradation characteristics were observed in all principal axes. The study showed that the fatigue profile is affected by raster orientation which strongly influenced the filling pattern. It was observed that the final parts lose some amount of their ductility during the manufacturing process which allows for the potential refinement of the existing material properties (Lee and Huang 2013).

The effect of deposition orientation on material properties and failure criteria of PC was studied. The study revealed that the failure mechanism maps show different failure modes such as tensile and shear failure for the specimens having different raster angles (0–90° with an interval of 15°). The material exhibits the highest hardness in the 0° and 90° specimens. It was also observed that the material exhibits lower elongation, tensile and yield strength when the failure mechanism is due to welds when compared to that of the beads (Hill and Haghi 2014).

Owolabi *et al*. (2016) performed studies to understand the response of ABS components fabricated using FDM under impact and high strain rate loading. It is revealed that all the tensile testing specimens are brittle in nature with consistent modulus of elasticity. During dynamic compression, the phenomenon of multi-stage contraction and expansion was observed at different strain rates until finally decreasing to a single stage at a strain rate of 2000^{-1}. It was observed that the failure initially begins with buckling and crushing with increasing strain rate beyond 1000^{-1} and complete failure was observed at 2000^{-1}.

Afrose *et al*. (2016) studied the impact of raster orientations on fatigue behaviour of PLA processed using FDM. The experiments showed that samples built in 45°-orientation displayed a more number of fatigue cycles, cycle softening and modulus of toughness than the samples built in both *X* and *Y* orientations. The results showed that the UTS of samples is the highest in the *X*-orientation at 38.7 MPa as roads are aligned with the applied load when compared to *Y* and 45° orientations.

The impact of critical parameters on the FDM part quality using the Taguchi method was investigated. It was found that the contribution of interactions between speed of deposition and layer thickness, speed of deposition and raster width towards part quality was minimal. Taguchi's technique analysis, analysis of variance (ANOVA), correlation analysis, signal-to-noise ratio (*S*/*N*) and regression analysis were used in this study. This study revealed that layer thickness is the most important contributor towards surface roughness as compared to the speed of deposition and raster width and parameters such as surface roughness and layer thickness are inversely related to each other (Anitha *et al*. 2001).

Study was conducted to find the optimal process parameters for the FDM machine that produces ABS components. In this study, the Taguchi method, *S*/*N* ratio and ANOVA are used to obtain optimum process parameters. It was found from the experiments that process parameters such as layer thickness, raster angle and air gap remarkably affect the elastic performance of the ABS components (Lee *et al*. 2005).

Torres *et al*. (2016) studied the impact of production parameters on the mechanical properties of the specimens made of PLA using FDM. It was observed that the most important settings that affect tensile strength are high density and high layer thickness. It also revealed that higher temperature increases strength due to the increase in cohesiveness between the layers. The study showed that in order to use low density or infill setting to save the material, the perimeter layers can be increased to increase the overall strength of the component.

The mechanisms that control the bond formation and quality between the adjacent filaments in FDM process were investigated. The experiments assessed the bond quality on the basis of the growth of neck formation observed between adjoining filaments. The results revealed that the envelope temperature and convective heat transfer conditions of the heating chamber have a significant impact on bond quality. This study suggests that better monitoring of cooling conditions may result in unintended consequences on mechanical properties and dimensional accuracy of the final product. Experiments showed that creep deformation and molecular diffusion are important in predicting bond quality (Sun *et al*. 2008).

Castro *et al*. (2016) demonstrated the 3D-printed Ku band antennas and microwave devices using cyclo-olefin polymer (COP)-based composites using FDM. COP has advantages such as high melting, high glass transition temperature and chemically inert when compared to ABS. The study revealed that high thermal conductivity and ultra-low loss COP composite material have a high potential for use in high-performance radio frequency 3D microwave devices.

Polymer matrix composites

The contribution of MFI and optimised MFI in the FDM process for Nylon 6–Fe composite material by varying the quantity of the reinforcement was investigated. In this study, the parameters such as proportion of filler material, temperature and load of extrusion are studied using Taguchi's L_9 orthogonal array technique. The study revealed that major contributors to MFI are extrusion load (45%), proportion of filler material (25%) and extrusion temperature (20%). This study was concluded by optimising the parameters so that MFI of Nylon 6–Fe becomes equivalent to MFI of the ABS material (Garg and Singh 2016).

Singh *et al*. (2016b) developed an alternative FDM material filament (Al_2O_3 powder in Nylon 6) for manufacturing wear resistant material and structures. The study revealed that due to the addition of Al_2O_3 as reinforcement in Nylon 6 polymer matrix has enhanced the wear-resistant properties of composite material significantly and the process shows high potential of producing the wear resistive parts which are comparable to industrial standards.

Boparai *et al*. (2016b) studied the effects of dry sliding wear behaviour of the FDM parts made of Nylon 6–Al_2O_3 composites. Wear testing is performed using pin-on-disc experiment. The study revealed that the wear resistance of the composite material is higher compared to ABS and concluded that adhesion and abrasion wear mechanisms are mainly responsible for the composite material. The temperature rise during testing and friction coefficient is lower for the composite material than the ABS material.

Singh and Singh (2015c) studied the wear modelling of Nylon 6–Al_2O_3 composite material which is made by FDM-assisted investment casting (IC) using Buckingham–π dimensionless analysis. The study used the Taguchi L_{18} orthogonal array and ANOVA to develop a mathematical model. The study concluded that the wear mainly depends on the density and volume of FDM-reinforced pattern.

The dimensional accuracy of the aluminium matrix composites made by FDM-assisted IC using nylon–6 waste-based reinforced filaments and optimised using the Taguchi L_9 orthogonal array technique was investigated. The study concludes that dimensional accuracy strongly depends on the length of a basic dimension (Singh *et al*. 2016a).

Singh and Singh (2015a) investigated the dimensional accuracy of the components made from an FDM filament having different amounts of Al and Al_2O_3-reinforced Nylon 6 matrix using a statistically controlled solution of FDM-assisted IC. The study resulted that the castings obtained using reinforced FDM material patterns are acceptable as per ISO standards UNI-EN-20286-I (1995). The study concludes that the process followed for making alternative FDM filaments is under statistical control as per the obtained C_p and C_{pk} values.

The effects of process parameters on micro hardness and optimisation of extrusion parameters of Al–Al_2O_3–Nylon 6 composite materials were studied. The *S/N* ratio concludes that the micro hardness is significantly influenced by the process parameters such as barrel finishing weight, filament proportion, density and volume of reinforced pattern, barrel finishing time and number of IC slurry layers (Singh and Singh 2015b).

The extrusion parameters such as mean barrel temperature, material composition and die temperature were studied and also optimised using the response surface methodology (RSM) technique with the help of MINITAB 17 software. The study also includes the dynamic mechanical analysis performed on the filament fabricated with the obtained optimised extrusion parameters which resulted in adequate stiffness (Boparai *et al*. 2016a).

A new composite material (Fe powder in nylon matrix) was developed for rapid tooling using FDM. The study revealed that the size of the filler particle and volume fraction of filler material played a remarkable role in establishing the upper limits of the mechanical properties. The newly developed material is suitable for processing using the FDM system for direct rapid tooling applications, and injection moulding tool inserts of good quality are produced successfully (Masood and Song 2004).

Polymer ceramic composites (biocomposites)

The impact of printing width on the mechanical properties of wood bio-composites by modifying the porosity of the material was investigated. The study revealed that increasing printing width (overlapping of filaments) increases the porosity but reduces the cohesiveness which leads to reduced tensile strength and increased water uptake capacity (hygroscopic properties). The study concludes that printed samples of FDM can provide materials that are appropriate for a range of moisture-generated actuation functionalities in bio-composites with enhanced mechanical properties as compared to compression moulded (CM) samples (Duigou *et al*. 2016).

Kuo *et al*. (2016) successfully prepared thermo plastic starch (TPS)/ABS copolymers biomass alloys blended with compatibilisers, impact modifiers and pigments and evaluated their feasibility for 3D printing applications. Experimental results revealed that physical properties of 3D-printed filaments such as thermal resistance, mechanical properties, emissions of volatile organic compounds and flow ability are superior to the commercially available ABS. De-branching and plasticisation processes are used to obtain high process ability of TPS.

Drummer *et al*. (2012) evaluated the suitability of PLA/tri-calcium phosphate (TCP) and the performance (mechanical properties) of parts manufactured using the FDM process. It was found that the level of crystallinity and morphology in the TCP are affected by the processing temperature which also affects its biodegradability. The study also revealed that the mechanical properties directly depend on the part size due to better dimensional accuracy and compactness of the part.

Sabino *et al*. (2013) studied the biocompatibility of the biodegradable polyester scaffolds of materials such as PLA and PCL which are fabricated using the FDM process. A software called Rhinoceros® version 4.0 was used in this study. The experimental results revealed the cyto-compatibility of the scaffolds by both cell adhesion and proliferation of cells on their surfaces that are the key requirements for tissue engineering applications.

Espalin *et al*. (2014) fabricated customised patient-specific implants of PMMA using the FDM process and examined the effect of fabrication conditions. Fabrication conditions such as layer orientation, tip wipe frequency and air gap are studied. The study concludes that the samples with high tip wipe frequency, high transverse orientation and low air gap have higher compressive strength and modulus.

Lei *et al*. (2007) studied the degradation behaviour of biodegradable and bioresorbable PCL–20% TCP composite scaffolds for bone engineering applications using SBF. The study showed that the degradation of scaffolds was slow which is required for tissue engineering applications. Biochemical assays and scanning electron microscope (SEM) studies revealed the formation of calcium-rich apatite (inorganic bone) layer on the surface of the scaffolds showing the bioactive nature which is needed for bone regeneration process.

Innovative manufacturing methods were developed which can process ceramics and metal–ceramic composite materials for bio-medical applications. The study used co-manufacturing, i.e. a combination of different technological approaches were successfully combined for processing different materials such as ZrO_2, steel and different morphological structures are manufactured. The study combined different AM technologies such as lithography-based ceramic manufacturing and freeze foaming that resulted in a biocompatible structure combining both dense and porous areas in one single part (Ahlhelm *et al*. 2015).

Development and fabrication of controlled porosity PP/TCP composite material using the FDM process were conducted. Samples used in this study had a pore size of 160 µm and porosities of 36%, 40% and 52%. The results showed that the best mechanical properties were obtained with samples having a pore volume of 36% and a pore size of 160 µm under compression loading. The tensile tests conclude that the UTS of PP/TCP composite is much lower than that of PP due to the addition of processing aids such as wax and plasticiser to the composite (Kalita *et al*. 2003).

Nanocomposites

A conductive 3D nanocomposite-based material PLA and multi-walled carbon nanotubes (MWCNTs) using liquid deposition modelling (LDM) were fabricated and the optimal processing conditions were found. The study revealed that electrical conductivity showed a significant increase with the increase in the proportion of MWCNT as compared to PLA. The study shows that the LDM method is highly reliable as conductive features of 100 µm can be reproduced (Postiglione *et al*. 2015).

Francis and Jain (2016) investigated the development and processing of ABS/nano-clay nano-composite material for the FDM process. The mechanical properties such as modulus and tensile strength have shown the same trend. With an increase in weight (wt) loading from 5% wt to 10% wt both modulus and tensile strength have increased, but with a further increase to 15% wt the properties decreased. The study revealed that the elongation at break is the highest for 5% wt and 10% wt batch-loaded parts displayed an increment of 24.6% in compressive strength and 6.5% increase in hardness as compared to ABS material.

Dul *et al*. (2016) developed ABS graphene nano composite material for the FDM process using melt compounding and extrusion. The study revealed that the properties such as deformation at break and tensile strength were severely reduced in the specimens made along the perpendicular direction, whereas only a slight reduction is found in both horizontal and vertical specimens due to the addition of graphene. The filler content in the nanocomposite is optimised to 4% due to the issue of flow ability. The study proved that the addition of graphene nanofillers reduced the coefficient of thermal dilation and creep compliance.

A nanocomposite material for the FDM process by reinforcement of PLA with graphene and MWCNTs was developed. The thermal properties, fracture surfaces using SEM and mechanical properties such as impact strength and tensile strength were studied in this work. The results from the quantitative analysis showed that there is minor improvement in the mechanical properties for both graphene and MWCNTs with the greatest increase found at 0.2% loading and 0.1% loading, respectively. Differential scanning calorimetry (DSC) tests revealed that there is no change in thermal properties such as glass transition temperature and melt temperature for both the composites (Plymill *et al*. 2016).

Fibre-reinforced composites

The effects of moulding temperature and fibre content on the flexural properties of PLA reinforced with bamboo fibre were investigated. In this work, the biodegradable composite is prepared using the emulsion-type biodegradable resin technique to achieve high fibre volume. The study concludes that the optimum values for fibre content and molding temperature are 70% and 160°C, respectively, which resulted in a flexural strength of 273 MPa and a flexural modulus of 6.8 GPa. The flexural strength of the composite increased up to 160°C but decreased after 180°C, whereas flexural modulus increased up to 140°C and thereafter remains constant. Both the properties enhanced with an increase in fibre content (Ochi 2015).

Sia *et al*. (2014) studied the interfacial fracture toughness of PLA and the oil palm empty fruit bunch composite material. In this work, surface treatment with NaOH solution is performed to enhance the interfacial bonding of the composite. The study revealed that interfacial fracture toughness, interfacial shear stress and surface roughness increase with an increase in the concentration of NaOH solution and time span of the alkali treatment. It was observed that the interfacial fracture toughness depends on matrix length, whereas interfacial shear stress has an inverse relation with bonding area.

Oksman (2000) studied the effects on the properties of natural fibre mat-reinforced thermoplastic (NMT). The composite used in this work was flax fibres reinforced with PP. The results revealed that the stiffness of the NMT composite material is comparable to glass fibre mat-reinforced thermoplastic (GMT) when measured with same or higher fibre content by weight. It was observed that the tensile and impact strengths of NMT are lower as compared to GMT, but showed an increase with an increase in fibre content. The NMT composite materials are highly anisotropic and showed poor adhesion between fibre and matrix.

Heijenrath and Pejis (1996) studied the impact of fibre content on mechanical strength and stiffness of NMT composite based on flax fibres and PP. It was observed that the stiffness of NMT is comparable with GMT at relatively low density of flax fibre. The study concluded that the strength of NMT is lower than that of GMT and there is no significant improvement in adhesion.

Zhao *et al*. (2015) studied the preparation of bamboo powder reinforced with PLA using material blending to produce 3D-printing filament. The study concludes that the bamboo powder size of 0.27 mm can avoid the clogging of nozzle as compared to having a diameter of 0.4 mm. The major parameters of the printer that were studied in this work are print speed, nozzle temperature, print thickness, coefficient of overburden, supporting angle and extrusion temperature.

The effect of process parameters on the interfaces and performance of 3D-printed continuous carbon fibre-reinforced PLA composites was investigated. The study revealed that with an increase in melting temperature the impregnation of PLA into carbon fibre improves which enhances the mechanical properties but when the temperature is increased beyond 240°C, the surface accuracy is affected. In this work, parameters such as hatch spacing, melting temperature, fibre content and layer thickness were optimised (Tian *et al*. 2016).

The effects of the FDM process parameters on tensile properties of CFRP were investigated. The results revealed that specimens having raster angles of 0° and 90° exhibited the highest Young's modulus, yield strength and tensile strength, whereas specimens with −45° and 45° raster angles have larger toughness and ductility. The study optimised the parameters such as infill speed of 25 mm/s, layer thickness of 0.15 mm for high tensile and yield strength, whereas 0.25 mm for high toughness and ductility. It was observed that the adhesiveness between carbon fibres and the ABS polymer matrix is poor (Ning *et al*. 2016).

Ning *et al*. (2015) studied the effect of adding carbon fibre to the ABS matrix in improving the mechanical properties of the composite material. The study concludes that adding carbon fibre increases Young's modulus and tensile strength but decreases the ductility, toughness and yield strength. The study showed that porosity is a major issue for the amount of carbon fibre that can be added to ABS matrix as adding 10% by weight of carbon fibre resulted in reduced mechanical properties. The study revealed that the composite specimens having 5% weight carbon fibre has larger flexural properties when compared with the pure ABS specimen.

Hofstatter *et al*. (2016) studied to understand the distribution and orientation of fibres in the parts made from carbon fibre-reinforced PLA composite using FDM. In this work, SEM, X-ray, tomography and magnetic resonance imaging techniques were used to analyse the fibre orientation. The study showed that the holes that are visible in SEM images are ellipsoid in shape with the major axis lying along the extrusion orientation and resulted in reducing the tensile strength. The study concludes that both longitudinally and transversely oriented fibres resulted in interconnected orientation.

Tekinalp *et al*. (2014) investigated the effects of process and fibre loading on highly oriented short carbon fibre-reinforced ABS composites using FDM. The results revealed that a significant porosity was observed in FDM samples as compared to CM samples. The results showed that the tensile strength of CM samples is larger compared to FDM samples which concludes that porosity has a dominant effect on tensile strength over fibre orientation. However, it was observed that fibre orientation is remarkably higher in FDM samples and hence can compensate the effect of porosity or poor interfacial bonding.

Zhong *et al*. (2001) studied the use of glass fibre-reinforced ABS (GF–ABS) composite as a feed stock filament material in the FDM process. The study concludes that the addition of glass fibres to the ABS matrix has significantly improved the mechanical properties such as tensile strength as compared to pure ABS, whereas it increased the brittleness and decreased flexibility of the composite material. This work showed that the limitations of GF-ABS composite can be improved by adding plasticiser and compatibilisers.

Results and discussions

From the literature review, it is evident that the development of new materials that are suitable/compatible with the FDM technology in increasing since the last decade. In the research studies, development of new material for FDM is done along with optimisation of the process parameters which is a critical criterion for achieving quality parts with enriched material, mechanical and thermal properties. Currently, there are different types of FDM machines available in the market with specifications regarding the flow ability of the material to be used for best results. Due to this limitation, many researchers while developing new material, initially studied the rheological properties and made the MFI of the new material equivalent to the specifications of the machine for better process ability. The effects of process parameters and inter-relation between two or more parameters should be studied thoroughly to improve the knowledge on mechanical and material properties of the FDM-processed parts.

Researchers have used various optimisation methods to study and optimise the processing conditions of the FDM process for development of various composite materials such as Nylon 6–Fe, Nylon 6–Al–Al_2O_3, PLA/TCP, PLA/carbon fibre, polymer-layered silicate composite, PLA/carbon nanotubes, ABS/starch, PLA/bamboo fibre, PP/flax fibre and ABS–graphene nanocomposites.

The Taguchi technique and ANOVA are widely used by the researchers as optimisation techniques as clearly found from the above-reviewed research work. The benefits of design of experiments using the Taguchi technique for fabrication of the FDM part using newly developed material includes the simplification of the experiment plan by reducing process parameters that need to be tested and feasibility to study interaction effects among different parameters (Anitha *et al*. 2001). Application of this technique helps in reducing cost and time of the experiments as it reduces the number of experiments to be performed in optimising the FDM process parameters for newly developed materials (Lee *et al*. 2005).

However, the major limitation/disadvantage of the Taguchi technique is that it does not include the changes that occur in environmental conditions and other noise factors (Pan *et al*. 2005). Researchers have also employed *S/N* ratios to measure the sensitivity of the quality characteristic such as surface roughness, print orientation layer thickness and raster width that are being investigated to those uncontrollable external or error factors in the experiment (Lee *et al*. 2005). From the research, it can be observed that ANOVA analysis is performed to identify critical process parameters or parameters that significantly affect quality characteristic of the FDM components. The significant input parameters which most researchers focussed are raster angle, air gap, raster width, layer thickness and print orientation.

Based on the literature review, various optimisation techniques such as the Taguchi method, ANOVA analysis, radiological imaging, DSC and RSM were applied for optimising FDM process parameters. The properties such as fracture strength and tensile strength of the materials that are developed for FDM are compared with the ABS material and extensive research is done for using these FDM parts directly in practical applications such as automobile and bio-engineering. Researchers are convinced that the Taguchi technique is dependable and is an efficacious approach in industrial applications to enhance the quality characteristics FDM part at low cost.

In the Taguchi method, the experimental scheme is put forward in terms of the orthogonal array which offers various combinations of parameters depending upon the goal of the experiment. The optimum parameters can be determined by different *S*/*N* ratios. However, in this Taguchi method, any two factor interactions among parameters can be used for emphasis of other two factor or higher interactions which may result in a non-optimal solution (Mohamed *et al*. 2014).

RSM is a combination of statistical and mathematical techniques to determine the optimum operating conditions by comprehending the impact of process parameters on the output part quality (Montgomery 2014). The RSM technique is the most promising and powerful optimisation method as it offers very low standard of error and has the ability to optimise many responses which is useful in optimising FDM process parameters. The effects of interactions among various process parameters can be clearly predicted by the RSM technique when compared with the Taguchi technique, and the RSM technique is more time consuming than Taguchi when dealing with optimisation of a large number of process parameters.

The DSC and thermo gravimetric analysis are used by researchers to determine the thermal variations such as glass transition temperature and heat flow characteristics and to check the thermal stability, respectively. DSC is used to study the change in thermal history of the material at different stages of the processing due to the effect of process parameters such as amount of filler material added and impurities. Fractography and morphological studies are performed by using SEM and optical microscopy to understand the microstructure analysis of the FDM material. Researchers used statistical process control and quality improvement methods to study the compatibility of the FDM process as per industrial standards by calculating C_p and C_{pk} values.

From the literature review, it is evident that polymer matrix composites, iron and aluminium powders are mostly chosen as reinforcement due to their ferromagnetic properties and high wear resistance and conductivity, respectively, which has wide applications in industry. In polymer ceramic composites and biocomposites calcium-based reinforcements with PLA and PMMA as polymer matrices are widely used for various biomedical applications such as bone grafting, artificial human organs, and their compatibility with the bodily fluids during their growth was studied. In this review, many naturally available fibres such as wood, starch, bamboo, jute, oil palm and flax were used as reinforcements with various polymer matrices. The mechanical properties obtained with these composites are found comparable with the glass fibre-reinforced polymers (GFRP) and hence there is a huge potential for replacing GFRP with natural fibre-reinforced polymers which also helps in producing products that are more environmental -friendly.

Research gap

FDM technology is newly evolving in terms of new application areas and improving the range of materials that can be processed using this technology. Based on the literature review, it is clear that different process parameters affect the quality characteristics of the final part obtained using the FDM process.

The characteristics of the FDM part such as tensile strength, compressive strength, flexural strength, dimensional accuracy, surface finish, hardness, yield strength, ductility, production time and cost are of primary importance to both manufacturers and customers. In the recent years, extensive research is done in optimising the process parameters so as to obtain improvement in mechanical properties, thermal properties, surface roughness and reduce material wastage and build time. There is always a trade-off between mechanical properties, processing time or part accuracy while working on FDM technology which makes it confined to customised or prototype parts and not suitable for mass production. The parts made through FDM are usually inferior to those that are made from conventional/traditional processes such as injection moulding in terms of both strength and accuracy, but complex shapes can be easily produced using FDM than conventional processes. In order to enhance mechanical properties of the parts produced using FDM, it is necessary to possess knowledge on the inter relationship between process parameters and their impact on the material properties. Most of the research works in recent years are mainly confined to the area of optimising the process parameters of the FDM process for standard materials such as ABS, PLA and PC; hence, there is a huge scope of improvements in the area of materials for the researchers to explore.

Most of the research is done for improving the mechanical properties of the FDM part which is made of the materials that are most widely used in FDM such as ABS and PLA by optimising one or combination of the process parameters. But in the recent years, due to the increased competition and technological advancements, researchers are working on developing new materials for FDM technology which increases the field of application such as tissue engineering and also improve the mechanical properties than the present materials.

Sufficient research has not been done on the interdependence of the process parameters on the material and mechanical properties for different kinds of materials that are used in the FDM process. Different researchers follow different approaches to evaluate a method for fabricating an FDM part with a newly developed material which is a matter of concern. Unlike the standards that are available in traditional manufacturing for different materials, there are no readily available standards for materials used in the FDM process. There is also a need to work on the FDM machine such as improving the range of melting temperature in order to include high melting point materials. Most of the research done on improving mechanical properties is carried out on the ABS material as it is commercially available at low cost, whereas very few researchers have concentrated on optimisation of process parameters for improving thermal and mechanical properties of the FDM fabricated parts using other materials.

As per available literature, not much research has been done considering environmental conditions such as temperature, humidity and noise factors which may affect the part accuracy. Most of the materials that are currently used in the FDM process such as ABS and PLA may get affected by these factors which may affect the dimensions of the FDM fabricated part. Hence, research should be done on various materials that are currently available and new materials that are going to be developed by considering the environmental factors.

There is a need to study the quality characteristics such as hardness, creep deformation, porosity (Harun *et al*. 2009), interlayer bonding (Harun *et al*. 2009), strain-rate loading (Afrose *et al*. 2016), molecular diffusion, process cost, product cost and production time. Recently, more research is carried on composite materials such as bio-composites, FRP's and polymer metal composites. Based on the literature review, mostly iron and aluminium powders are used as reinforcements in the polymer matrix. Hence, there exists a scope to work on dual filling, different kinds of filler materials, abrasives and their varying proportions for different tailor-made properties (Singh *et al*. 2016a). Due to the increasing environmental consciousness in the world, there is a need to do extensive research on natural fibre-reinforced composites as they have a huge potential in replacing glass-filled reinforced composites which are not environmental-friendly. Most of the researches available on natural fibres reinforced composites are having standard materials such as ABS, PP and PLA as polymer matrices. Hence, it is necessary to work on different combinations of natural fibres and polymers.

Conclusions

This paper presents a review on research works that are carried out on development of new materials and optimising the process parameters of the FDM process. By making more materials compatible with this FDM technology, the scope of using products manufactured using FDM for various applications will be increased and helps manufacturers to sustain the competition. Several research studies on optimising process parameters such as raster angle, air gap, layer thickness, build orientation and raster width for different materials were reviewed. This literature review also presents the work based on optimisation techniques such as Taguchi, RSM and ANOVA analysis which are successful for practical applications. This review shows that there is a need to develop optimisation methods and mathematical models to include environmental and noise factors which may affect the part accuracy as well as surface finish as current methods does not include these factors. This paper also identified the areas where further research needs to be carried out in optimising the FDM process and increasing the range of available materials for FDM.

The PMC materials are the most popular in industrial applications such as automobile, aerospace, marine, construction, electrical, sanitary and sports equipment due to their high strength-to-weight ratio. Development of bio-composites has brought huge technological advancements in the medical field by improving diagnosis methods and treatments. FDM makes use of bio-composites such as PLA/TCP and PMMA to produce body implants and scaffolds for tissue engineering. Nanocomposites made with graphene, carbon nanotubes, etc. as reinforcements are used in this technology for making windmill blades, aircraft components and light-weight sensors.

Recently, most of the manufacturing industries are focussing on developing infrastructure for executing research on FDM technology as it possess huge potential for changing the manufacturing scenario by generating huge profits without compromising on product quality. These future works will help in improving the FDM process further and making it an ideal AM process for various manufacturing applications including bio-medical with high part quality, dimensional accuracy and other desired properties. Overall, literature review revealed that current research is being done to increase the range of materials available for FDM and this range must be scaled up for future research.

Disclosure statement

No potential conflict of interest was reported by the authors.

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