ARTICLE IN PRESS

Materials Today: Proceedings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

A review on polymeric materials in additive manufacturing

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Polymeric materials
Additive manufacturing
Automotive
Drug delivery
Fabric industry

ABSTRACT

Polymers are the greatest innovation of the millennium. Due to their low price, ease of manufacture, resistance to water and versatility, polymers have several applications in different domestic and industrial sectors. Digital fabrication technology which is also referred to as 3D printing or additive Manufacturing (AM) is used for creating physical components from a geometrical representation by step-by-step addition of materials. This review paper elaborates on the use of polymers for Rapid Manufacturing. One such material used is Shape Memory Polymers that have been analyzed as Smart Materials (4D Printing Materials). Polymers such as Thermoplastics, elastomers, thermosets, and polymers with integrated fillers, bio-polymers, and polymers blended with biological materials come under the range of other polymeric materials used in AM. The quality evaluations that are performed are based on mechanical properties, part density and temperature stability. Polycarbonates (PC), acrylonitrile butadiene styrene (ABS), polyether-ester ketone (PEEK), polyetherimide (ULTEM) and Nylon are usually utilized polymers in measures which need thermoplastics, or plastics treated by warming to a semi-fluid state and near the softening point. Properties of materials were reviewed for example, Strength parameters of a specific list of Polymeric Materials used in 3D printing was revised, where strength tests showed that material such as Polybutylene terephthalate has a high Yield Strength and Polypropylene has a high Ultimate Tensile Strength. Special characteristics such as Water Solubility, Shape Memory and Corrosion Resistance were reviewed for the ability to choose the ideal material for its application. Impact on the Society, Environment and Economy, of 3D printing plastics was brushed up from previous surveys in order to understand the necessity of growth of this industry.

Selection and peer-review under responsibility of the scientific committee of the 28th International Conference on Processing and Fabrication of Advanced Materials.

1. Introduction

Additive manufacturing (AM) is basically 3D printing. Rather than simply using conventional machining techniques which include wastage of materials by removing unwanted fragments, additive manufacturing causes fusion of materials to bind them and create objects. It is comparatively a flexible technology that subtractive manufacturing. Since technology is advancing day by day, new materials are being created to have the right properties that can be applied to the right functions. This review paper mainly focuses on the characteristics of polymeric materials that had been produced and used by the AM industry and the impact on the market of AM. Since several kinds of polymeric materials are available, the manufacturer of the product would prefer the polymer with the optimum conditions for the required purpose. Mechanical properties for example, optimum strength for manufacturing and prototyping is required.

High elasticity is required for garment industry. A high thermal resistivity is required for insulation. Use of light weight polymers are for aerospace applications. Greater amount of ductility is required for wiring and circuitries. Increased toughness is required for supporting materials. An optimum melting point is essential for temperature-dependent environmental factors that are experienced by the polymeric substance used. A proper amount of flexibility is required for better portability of the material. A property called Shape memory has been exhibited by certain polymeric materials which have been discussed in this review which can be used for bridge structures and heat exchangers. Degradability of a material for an allocated period of time is required for the extended use of the material considering fatigue strength of the material. Chemical resistance is an important factor needed for manufacturing of apparatus in chemical industries. Water solubility is a property which is one of the essential properties of certain

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https://doi.org/10.1016/j.matpr.2021.02.485
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the 28th International Conference on Processing and Fabrication of Advanced Materials.

Please cite this article as: J.M. Jafferson and D. Chatterjee, A review on polymeric materials in additive manufacturing, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2021.02.485

polymeric materials that could be used for drug delivery and pharmaceutical applications to act as a carrier of the drug to the target cell.

Additional Manufacturing uses several methods to manufacture the component depending on the type of the material which needs to be used and the properties of the final component required as shown in Fig. 1(a). It has been inferred from the following literature survey that AM processes include Material Extrusion (ME) which includes the Fused Deposition Modelling (FDM) technique, Vat Photopolymerization, Material Jetting, Binder Jetting, Sheet Lamination and Directed Energy Deposition. Powder Bed Fusion (PBF) is a technology which includes methods like Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Selective Heat Sintering (SHS) that follow the same norm as PBF.

The process of FDM follows extrusion of a solid plastic strand which enters a nozzle-shaped filament head which is responsible to melt it and extrude it out as layers. The polymer material should be able to flow, easily fuse, and then harden quickly. Thermoplastic polymers that are amorphous in nature are the perfect materials that can be applied in this process because of their low thermal expansion coefficient, low melting temperature and less glass transition temperature, properties which can reduce internal stresses that include warping caused during cooling [1]. Amorphous thermoplastics cover impact-resistant polystyrene (HIPS), polystyrene (PS) and thermoplastic elastomers (TEP). Amorphous thermoplastics in their indigenous state are transparent. The objective of this review paper is to highlight the polymeric materials used by leading companies and their properties. Thus, this paper will be a mini knowledge database that helps young researchers and the engineers who develop 3D printable parts to select appropriate materials for their specific applications.

2. Polymeric materials used in AM industry

Polymeric materials-based machines contribute to 14.7% of 3D printing landscape. The Amorphous and crystalline polymeric materials are classified into general purpose, engineering grade and ultra-performance materials Fig. 1(b). The leading polymer base AM machine manufacturers are given in Fig. 1(c) and the top 20 global additive manufacturing market of 2020 is given in Fig. 1(d). AM has a huge market potential and its wiser to adopt to the latest developments in the field of AM,

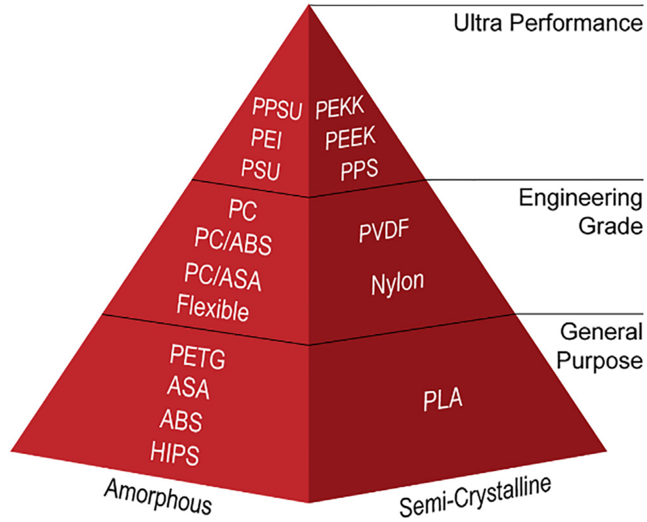

Fig. 1b. Different regimes pf polymeric materials used in AM.

2.1. Materials for Vat photo-polymerization based 3D printing techniques

The Vat photo-polymerization techniques use a UV curable resin. Each layer of the sliced CAD model will be solidified by selectively curing by UV light source. Stereo-lithography (SLA or SL) uses laser as light source. A beam of laser will be focused on the Vat bath and each layer will be 3D printed. Digital light processing (DLP) uses a projector screen to flash the image of a single layer at a time and it will cure it. Continuous Light Interface Production (CLIP) uses an oxygen permeable membrane below the resin, and there is no chance of resin getting adhered to the transparent window. It is 100 times faster than regular SLA and DLP processes. Daylight polymer printing (PPP) uses an LCD display and a special daylight polymer. Tensile strength is a property of the material under testing that shows its resistance to break during tensile loading. Tensile modulus indicates the resistance or rigidity of the material to elastic deformation, Elongation quantifies the plastic/elastic deformation of a material that is subjected to a strain, Flexural strength measures the resistance of a material to break when subjected to a bending load and Flexural modulus measures the rigidity or resistance of the material to bend. The stress strain

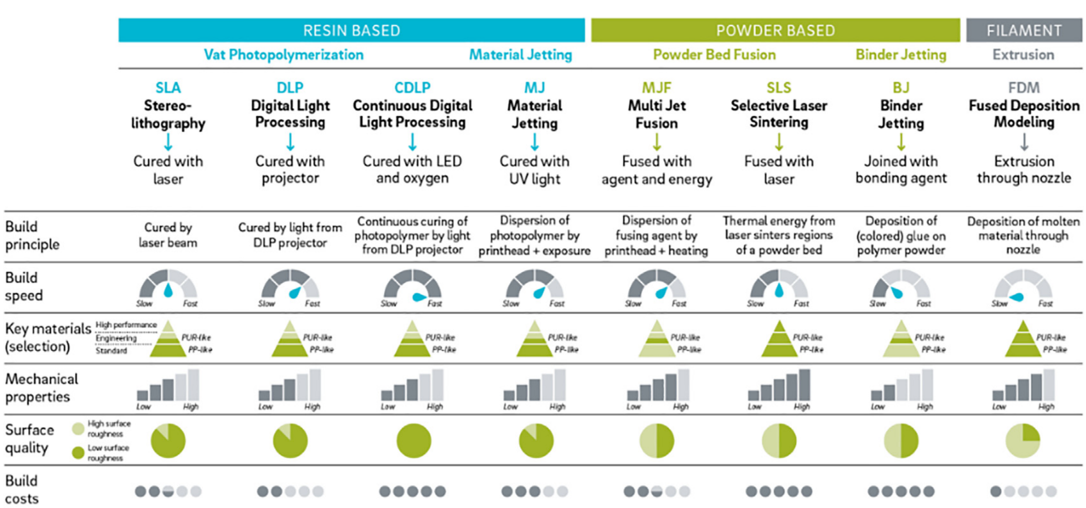

Fig. 1a. Polymer based AM processes (Image Source: Roland Berger).

Fig. 1c. 3D Printer Manufacturers (Image Source: AMFG).

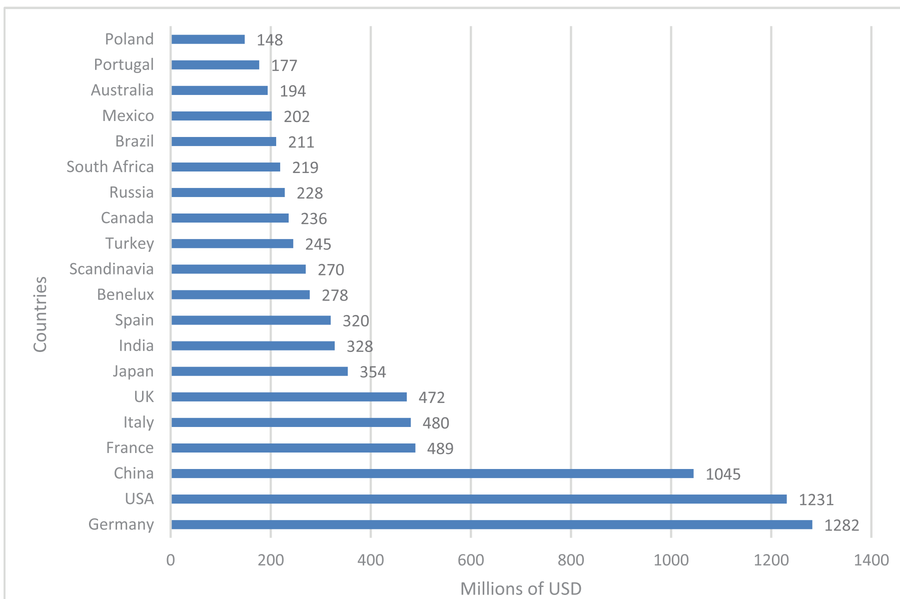

Fig. 1d. Global AM markets of top 20 countries (Image Source: 3dpbm/SmarTech Analysis).

curve of a ductile material and a comparison of stiffness behaviour in various common materials is shown in Fig. 2. The properties of most commonly used resins are given in Tables 1-4 and their corresponding plot of tensile strength vs flexural strength and density are shown in in Figs. 2-6. The visual appeal of few SLA/SL materials are shown in Fig. 7.

2.2. Materials used in Polyjet/Multijet processes

PolyJet/Multijet 3D printing process uses jetting thousands of UV sensitive polymer droplets on the building platform and solidifies it with UV light. Multijet and Polyjet are same, 3D Systems used to call their own MJ printers as Multijet and

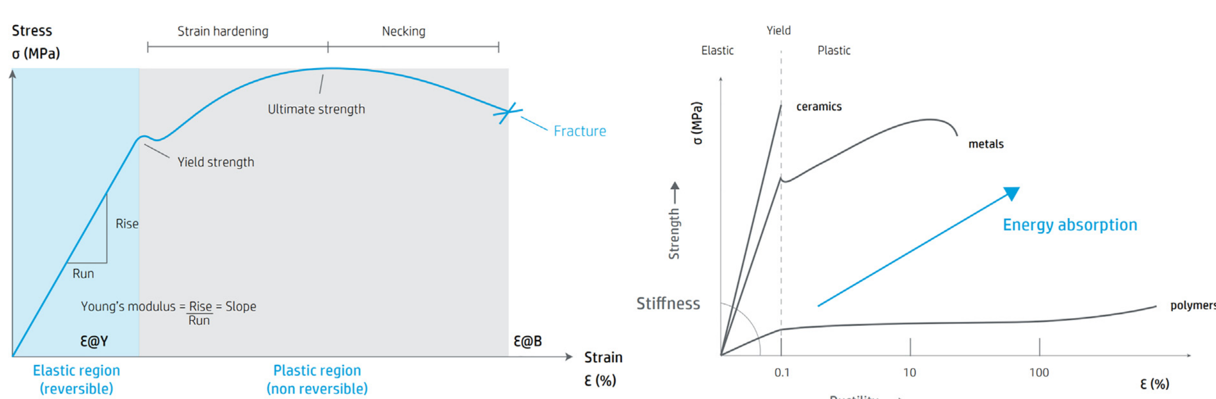

Fig. 2. General mechanical properties.

Table 1
Properties of Clear/Transparent resins.

1	Somos WaterShed XC 11,122	50.4	2770	68.7	15.5	1.12	25
2	3D Systems VisiJet SL Clear	52	2560	83	6	1.1	46
3	Somos Element	53	3170	114	2.3	1.11	22
4	3D Systems Accura Phoenix	53	2490	98	4	1.13	16
5	Prodways PLASTCure ABS 3650	55	2550	90	11	1.11	
6	Somos WaterClear Ultra 10,122	56	2880	84	7.5	1.13	25
7	3D Systems Accura 60	63	2895	94	9	1.13	20
8	Engineered Material Acrylic Clear	63	3000	113	15.5	1.17	15
9	3D Systems Accura Phoenix TPC	64	2780	130	4	1.13	20
10	Engineered Material PC Optical Grade	65.2	2300	94.2	110	1.2	710

Table 2
Properties of Composite resins.

		Tensile Strength (MPa)	Tensile Modulus (MPa)	Flex Strength (MPa)	Elongation at break (%)	Density (g/ cubic metre)	**Izod Impact (J/m)**
1	Prodwaya PLASTCure Rigid 10,500	60	7950	78	1.5	1.6	
2	3D Systems Accura CeraMax	61.5	9200	131	0.8	1.59	**13**
3	3D Systems Accura Bluestone	67	9650	139	1.9	1.7	**15**
4	Somos Perform	68	10,500	120	1.1	1.61	**17**
5	Somos Perform (TPC)	80	9800	146	1.2	1.61	**20**

Table 3
Properties of flexible resins.

1	Somos 9420	19	400	27	28	1.13	**46**
2	**Somos 9120**	**31**	**1350**	**45**	**20**	**1.13**	51
3	Engineered Material PP	33	1345	48	12	0.91	**48**
4	3D Systems VisiJet SL Flex	38	1620	57	16	1.14	**22**
5	3D Systems VisiJet SL 7840	41	1900	71	14.5	1.13	**48**
6	Engineered Material PBT	55	2700	80	20	1.24	**120**

Table 4
Properties of general purpose resins.

		Tensile Strength (MPa)	Tensile Modulus (MPa)	Flex Strength (MPa)	Elongation at break (%)	Density (g/ cubic metre)	Izod Impact (J/m)
1	3D Systems Accura 60	38	1625	56.5	16.5	1.13	22
2	Somos ProtoGen 18,420	43	2250	68.6	12	1.16	21
3	3D Systems ABS White SL 7810	43.5	2100	65.5	15	1.13	46
4	3D Systems VisiJet SL Black	45	2150	76	5	1.13	47
5	Somos ProtoGen 18,920	47.2	2210	74	16	1.16	23
6	Somos GP Plus 14,122	47.4	2510	67.3	7.5	1.16	26
7	Somos ProtoGen 18,120	53.3	2680	82.8	9	1.16	20
8	Prodwaya PLASTCure ABS 2800	62	3200	110	7.5	1.11	
9	3D Systems Accura 55	65.5	3290	99	6.5	1.13	17
10	Somos ProtoGen 18,420 (TPC)	67.1	2920	86.3	7.5	1.16	17
11	Somos ProtoGen 18,120 (TPC)	69	2950	90	7.5	1.16	19
12	Somos ProtoGen 18,920 (TPC)	69.4	2730	95.1	6.5	1.16	22
13	Engineered Material PG GF10%	68.9	4200	108.5	8	1.26	175

3D systems calls their MJ printers as Polyjet printers. These printers are more accurate and faster. Polyjet printing process is known for its very high surface quality compared to other 3D printing processes (Fig. 8). The microstructure of the 3D printed surface in a Polyjet machine before and after finishing operations is given in Fig. 9(a), (b), (c). The mechanical properties used in different material jetting processes are given in Table 5 (Fig. 10).

2.3. Materials for Multijet fusion processes (MJF)

Multi jet fusion uses no laser, it uses a fusing agent and UV heat source that makes the fusing agent to absorb more heat than the parent powder, thereby fusing the powders together. Then a detailing agent is applied to the areas were the fusing agent is applied, that helps in creating fine details like sharp corners and specific colouring Fig. 11.

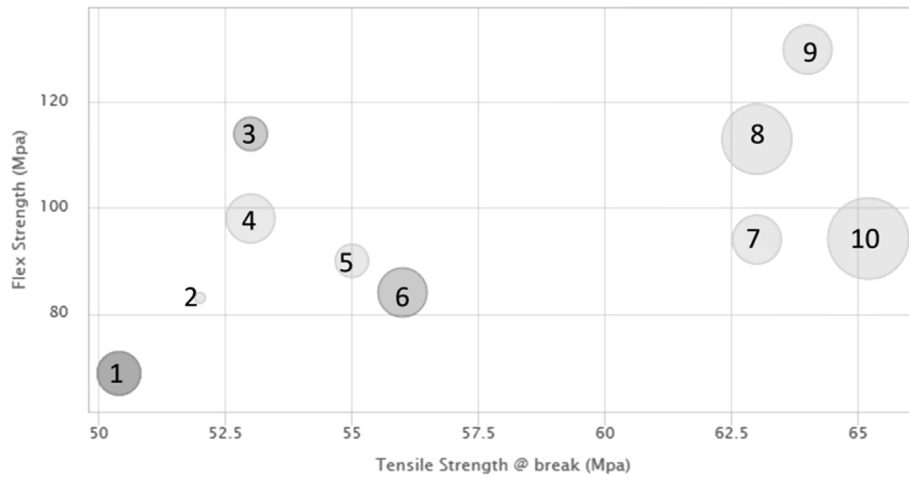

Fig. 3. Tensile strength vs flexural strength and density (Balloon size) of clear/transparent resins Material numbers 1 to 10 correspond to the list given in Table 1.

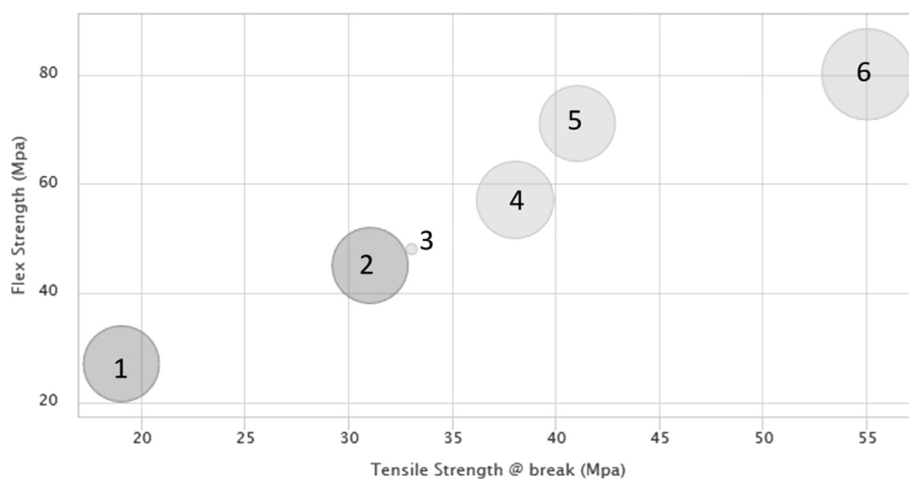

Fig. 4. Tensile strength vs flexural strength and density (Balloon size) of composite resins Material numbers 1 to 6 correspond to the list given in Table 2.

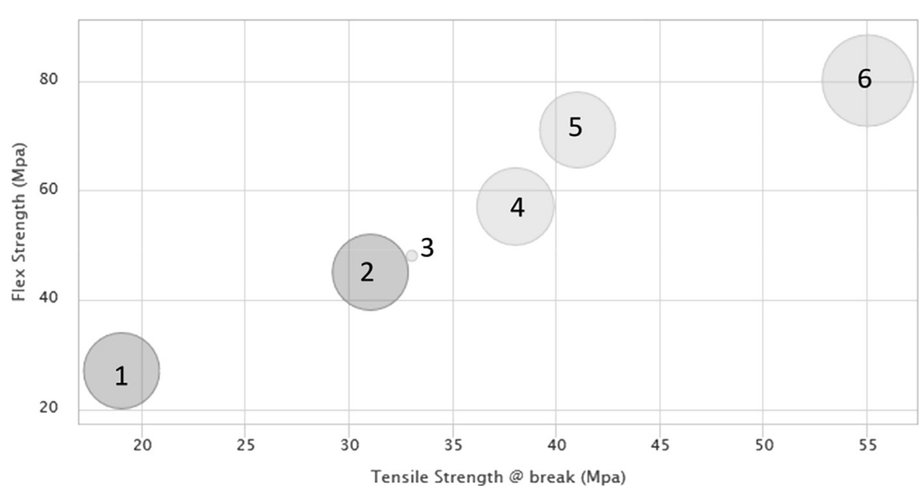

Fig. 5. Tensile strength vs flexural strength and density (Balloon size) of flexible resins Material numbers 1 to 6 correspond to the list given in Table 3.

Surfaces with embossing and various texturing can be easily made with this process. Very thin walls of even 1 mm is possible with this process and live hinges of 0.5 mm can be easily made. The production capacity of HP Multi Jet fusion machines are higher than FFF and laser sintering processes. For a printing time of 38 min it can produce 12,600 gears, however laser sintering can

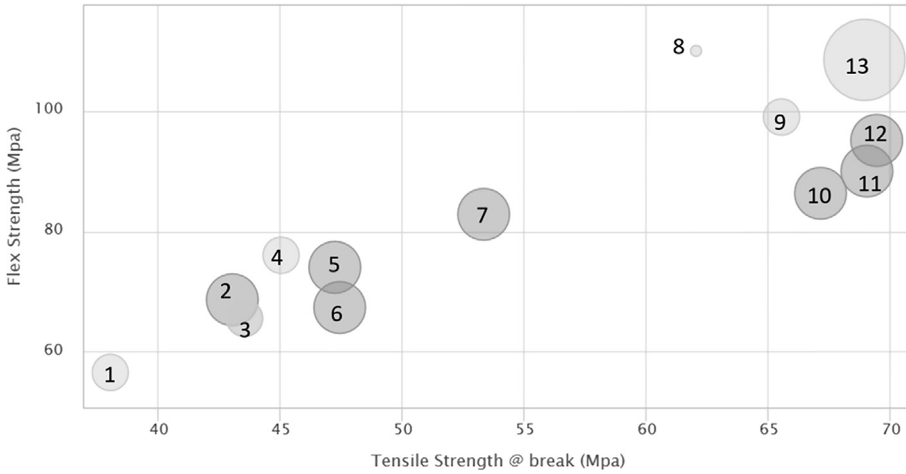

Fig. 6. Tensile strength vs flexural strength and density (Balloon size) of general purpose resins Material numbers 1 to 13 correspond to the list given in Table 4.

Fig. 7. Visual appeal of few SLA/SL materials.

produce only 1000 gears and FFF can produce just 460 gears of same size. MJF can directly print surface textures and embossing on the surfaces as shown in Fig. 12.

HP Fusion Jet has materials such as HP high reusable PA12, Ultrasint TPU 90A, CB PA 12 HP high reusable PA11, HP high reusable PA 12 Glass Beads (GB), HP higher re usability PP. PA12 is one of the most useful engineering-grade plastics available. It is utilized across all major industries and for a wide range of challenging applications. PA12 is mechanically strong, heat-resistant and bio-compatible. It has good chemical resistance with chemicals such as alcohol, concentrated / diluted alkalis, Ethers, Esters, hot water, ketones, motor oil, aliphatic hydrocarbons, dot 3 petrol, and toluene. HP Fusion Jet PA12 is printed extremely fast, at a very high resolution and at high-accuracies and is therefore not only used for functional prototypes, but also for short-run manufacturing of fully functional parts. It is suitable for very complex parts like human skeleton and intricate parts with moving components. BASF has developed Ultrasint TPU 90A material (Fig. 13) for HP s Multi Jet Fusion machines and it has high wear resistance, good mechanical properties, rubber like elasticity with shore hardness of 90A and excellent durability. CB PA 12. is a material for multi-colour 3D printing (Fig. 14). HP Multijet fusion and Polyjet technologies produces surfaces with less Rz values in terms of roughness (Fig. 15).

2.4. Materials used in laser sintering processes

Laser sintering (LS) uses a laser source to heat and fuse the powder particles together. The polymeric powders used should have a uniform size in the range of 50 to 90 μm. The density of the 3D printed part is directly affected by the particle shape. Perfect spherical powder particles can produce parts with higher density due to their good packing ability. The manufacturing methods determine the shape of the particles Fig. 15. The important properties of LS polymers are shown in Fig. 16. The material domain for LS is dominated by polyamide based powders. The most commonly used LS powders are compared are listed and compared in Fig. 17. Sample LS printed parts are shown in Fig. 18 .

2.5. Materials used in FFF/FDM processes

FDM/FF uses a plastic filament as the input material wire to deposit it Stratasys is the leader in FDM based technologies. They use their own proprietary materials in their machines. They have a range of materials for FDM, Stereolithography, SLS and MJF 3D printing processes. Stratasys has provided a materials wizard in their website from which the users can select appropriate materials for their specific applications. The polymeric materials used by Stratasys are listed in Table 6. Sample FDM printed parts for visualization are given in (Figs. 21-23) and the comparison of material

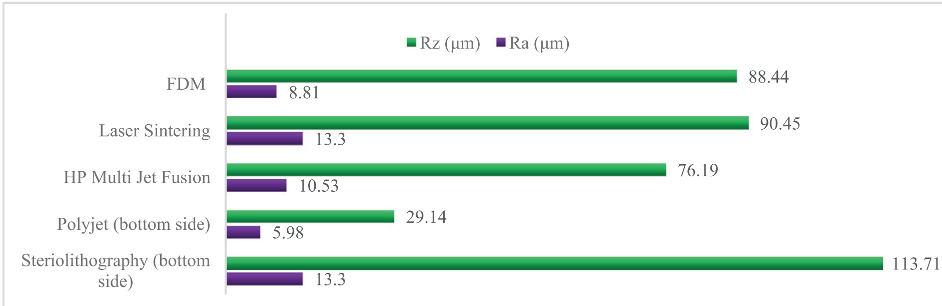

Fig. 8. Surface roughness comparison of 3D printing Processes (Image Source: 3Faktur).

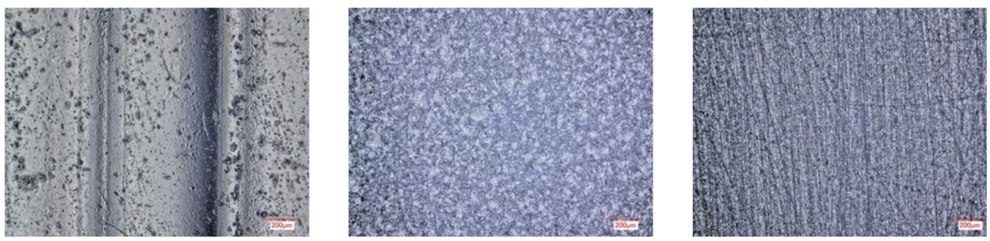

Fig. 9(a) 5As-printed Ra:6 µm, Rz:29.1 µm

Fig 9(b) Blasted with $Al2O_3$ Ra:3.7µm, Rz:24.2 µm

Fig 9(c) Grinded Ra:0.2µm, Rz:1.7 µm

Fig. 9. (a) 5As-printed (b) Blasted with $Al2O_3$ (c) GrindedRa:6 µm, Rz:29.1 µm Ra:3.7 µm, Rz:24.2 µm Ra:0.2 µm, Rz:1.7 µm Surface microstructure of Polyjet 3D printed sample using Veroblack material (Image Source: 3Faktur).

Table 5
Properties of the materials used in various MJ processes.

	Tensile strength (MPa)	Elongation at break	Flexural modulus (MPa)	HARDNESS (SHORE D)
VeroWhitePlus	58	10–25%	2700	85
PolyJet GreenFire	57	25–40%	1000–2200	86
VeroBlue	55	15–25%	2200	85
VeroGrey	58	10–25%	2700	85
PolyJet Amber Clear	58	15–25%	3000	85
Endur (RGD450)	42	20–35%	1500–1700	80–84
PolyJet Flex & Over-Mold	2	25–220%	_	27–95
Nylon PA11	48	36.5 ± 8.5		
Nylon PA12	45 ± 3	20 ± 5		

properties of FDM and Polyjet 3D printing materials are provided in (Fig. 24).

Solvey has its materials that are already travelling the outer space for at least 50 years. In airplane more than 50,000 metal fasteners are used. If we replace them with Solveys specialty polymers, 50% of weight can be save in terms of aluminum fasteners and 80% for steel fasteners. One good example is in 1965 this group developed a material: Udel polysufone" polymer that was used to make the visors of the space suits used by Neil Armstrong and Buzz Aldrin. This transparent material is tough and can withstand high temperatures. The progress of Solvay has put them as a potential choice for aerospace, healthcare, water, electronics construction and consumer goods. Solveys high performance filaments (Fig.19) and powders for additive manufacturing has higher strength, chemical and flame resistance. Also these polymers are light weight, corrosion free and light weight, thus they can be used as a replacement for metals. Solvays PEEK material "KetaSpire PEEK XT" is the first of its kind with high temperature resistance, high stiffness, high strength and superior performance at elevated temperatures and pressures. PEEK has 2:1 of ether to ketone (Fig. 20) that gives the polymer better chemical resistance and processability. Other Polyketones like PEKEKK, PEKK and PEK, that are used in high temperature applications alters this ratio and because of that they don't have good corrosion resistance property.

3. Drug delivery

There are several benefits of using polymeric materials for 3D printing in Health care industry. In relation to other materials for instance Ceramics, Metals, and Composites which are conventionally used for additive manufacturing, Polymers generally are comparatively simpler to create and comprise of properties that can be easily adjusted by changes in composition. The factors needed in an ideal carrier of drug to the target cell should include properties like Water Solubility and Hydrophobicity, Biocompatibility, Nano size, Strength, Non-toxicity, feasibility and ease of manufacture. It has been inferred that Bone Drug Delivery systems are based on polymers that are soluble in water which can transport drug directly to bone without causing any other side-effects and tissue rejection. Optimization of the carrier polymer is also an essential factor in the growth macromolecular therapeutics that include of bone-targeting. There are several natural polymers available but artificial polymers are preferred, since natural polymers for exam-

Fig. 10. Visual appeal of *Polyjet/Multijet* materials.

ple Collagen and Gelatine more often require cross-linkers which could turn up to be cytotoxic [2]. In a study conducted about the creation and categorization of the conjugates of poly(2-ethyl 2-oxazoline) along with proteins and drugs [4], it was provided that Monomethoxy(polyethylene glycol) (mPEG) having amphipathic properties i.e. having both hydrophobic and hydrophilic portions, show certain advantages for instance improved solubility properties of drugs that are insoluble in water and similarly of enzymes and chemicals in natural organic solvents, when these are utilized as biocatalysts.

3.1. Water soluble

PPolymers that are water soluble include Polyvinyl Alcohol (PVA), Polyurethane (PU), Hydroxypropyl Methylcellulose [3], Monomethoxy(polyethylene glycol) (mPEG) [4]. In a patent invented by John Lang Lombardi, Dragan Popovich, Gregory John Artz, all of Tucson, Ariz, was based on water soluble materials used as support and mold material [5] obtained that poly(2-ethyl-2-oxazoline), now referred to as PEO, can be used as a material used as a support which can be used for additive manufacturing processes for rapid prototyping for instance, in extrusion freeform fabrication or a fused deposition modeling. The properties of PEO that outweigh other materials include high strength, rigidity of the thermoplastic polymer, and optimum slump resistance for temperatures less than 200 °C. It has also been proven that PEO is an amorphous polymer which has an insignificant amount of shrinkage when solidified.

In the literature review [6] conducted in order to find the materials which exhibit water solubility by Allison M. Pekkanen, a class of poly(ether ester)s characterizes the properties which include water-solubility, polymers containing ions which combine to show sufficient mechanical properties for efficacious material extrusion at low temperature. Dynamic analysis of mechanical and tensile strengths discovered a petty variance in mechanical properties for these Quantitative ion exchanged polymers lower than the melting temperature, signifying an unimportant change in the properties of the final part.

4. Automotive industry

Introducing the custom of 3D printing in the product development cycle and the manufacturing sector of the automotive industry, reduces the amount of material wastage that are more likely to occur while using conventional machining processes. The research conducted on the environmental impacts and assessment of using additive manufacturing in the automotive industry [7] elucidate on conventional machining processes for instance, Aluminium casting, Iron casting, High-alloyed steel part machining and Steel low-alloyed cast part machining, which release an estimated amount of scrap rates which are 10.4%, 6.04%, 47.1%, and 60% respectively. It was also concluded in [7] that improvements on

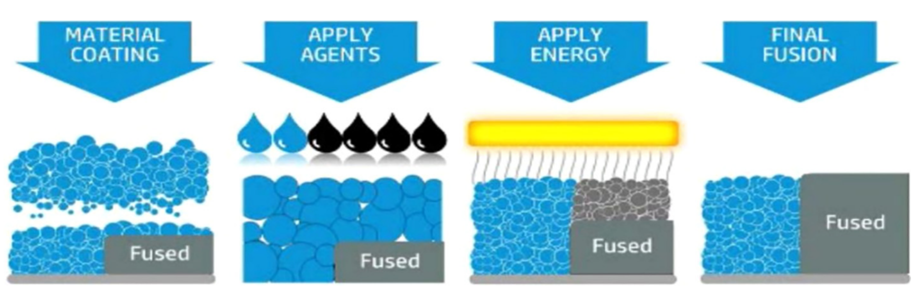

Fig. 11. MJF Technologies (Image Source: 3Faktur).

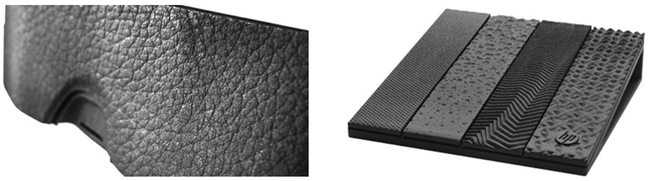

Fig. 12. Application Examples showing the surface texturing/embossing capability of MJF Technologies using PA12 material (Source: Materialise, HP).

Fig. 13. Parts printed using Ultrasint TPU 90A (Image Source: 3Faktur).

Fig. 14. Multi-colour Parts 3D printed using CB PA 12. PA12 (Image Source: 3Faktur).

the environment are consistent when thought about the future implications of this technology. The motives behind this expectation are the potential of AM in reducing weight if the manufactured component, only if clean electricity is being used for the process of 3D printing. Due to the governmental and consumer demands for light weight, fuel efficient vehicles, there is an increase in the use of lightweight plastics and composites in the automobile industry [8]. When diving into the automotive sector, one needs to keep in mind the properties which need to be appropriately selected for a robust use of the manufactured product, and these properties reflect on the type of material chosen. The parameters which come most effective include greater thermal, mechanical and chemical resistance, ease of manufacture, durability, cost of production and feasibility of the material [8]. Certain benefits of using materials of plastic in automotive include lower corrosion for a longer shelf life, ability to create intricate geometry, flexibility while fitting for assembly, safety and ergonomically efficient, and the ability to be recycled [9]. The polymeric materials that have been suggested in the research [14] are Polycarbonates, Acrylonitrile butadiene styrene (ABS), Polyamide (PA, Nylon-6/6, Nylon-6), PVC (Polyvinyl chloride), PP (Polypropylene), PUR (Polyurethane), PS (Polystyrene), PE (Polyethylene), POM (Polyoxymethylene), PMMA (Acrylic), PBT (Polybutylene-terephthalate), PET (Polyethylene-Terephthalate), and ASA (Acrylonitrile-Styrene-Acrylate). Although the applications of each material have been suggested separately, yet their mechanical properties that make them fit for this use is not shown in a quantitatively unambiguous sense. In order to carry on with the study, a quantitative route has been taken in this paper to certify the aforementioned materials for selection.

4.1. Yield strength and Ultimate Tensile strength

Yield Strength is the point, which when determined, provides the limit after which the material starts to undergo everlasting deformation, and the material is unable to return to its initial physical configuration. Similarly Ultimate Tensile Strength (UTS) is the limit up to which the polymeric material can withstand the ripping upon application of a tensile force. The polymeric materials should show a high amount of yield and tensile strength. The following (Table 7) shows the range of Yield Strength and Ultimate Tensile Strength of the polymeric materials used in the automotive industry. Nylon 12 carries the strength of impact and durability essential for functional testing. Tensile and flexural strength merge to create robust prototypes, with the flexibility associated with many thermoplastics that are under production. Glass filled variation of Nylon 12 have properties, for example, more prominent rigid nature, which are immaculate while prototyping inflexible bits anticipated assembling in cutting edge designing of thermoplastics, and is the exact choice for functional testing. Structure, fit and functional testing would now be able to be finished without penance. The filler is glass globule and not fibre; part transcendently increments in stiffness yet not strength. Synthetic manufactured filaments that are normally utilized in industry are carbon fibre-fortified polymers (CFRP). They are comprehensively utilized in the Airbus A350 airplane, segments in the car business, blades of the wind turbine, and endoscopic medical procedures. Carbon nanotube (CNT) composites in a polymer framework were been surveyed which demonstrated that the article didn't elucidate on AM by means of CNTs. CNTs will in general connect a tensile strength between a range from 100 to 600 GPa and Young's moduli inside a scope of 1 to 5 GPa. These properties lead to the conclusion on how essential it is to spend in a good interface between the CNTs and the neighbouring matrix [10].

Out of the following materials that were listed in the above table, the material showing greatest Yield Strength is PBT (Polybutylene terephthalate), the material showing greatest achievable Ultimate Tensile Strength is PP (Polypropylene). Henceforth, if greater strength is the requirement with applications such as in automobile body closures, energy absorbing areas.

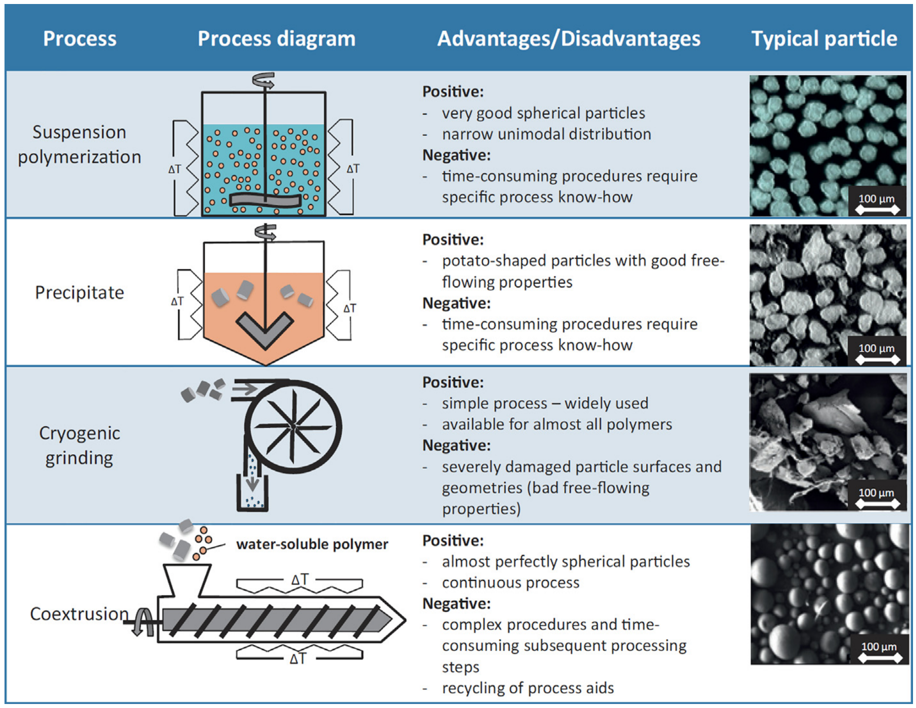

Fig. 15. Powder particle shape w.r.t their manufacturing processes (Image Source: Processes, and Materials, 2018).

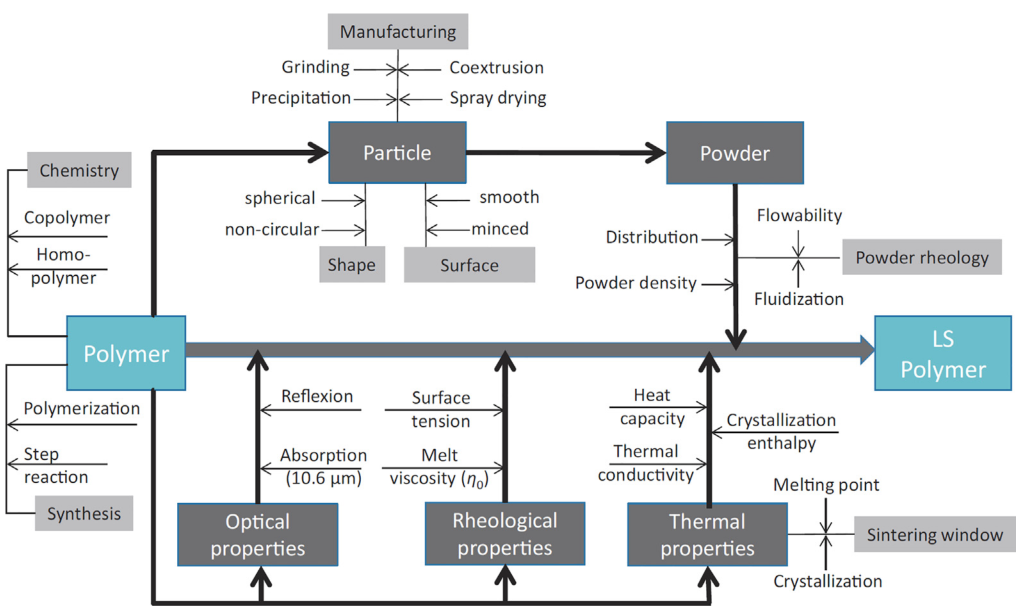

Fig. 16. Important properties of LS powders (Image Source: Processes, and Materials, 2018).

4.2. Flexibility

A study on the flexibility of polymers compared to metals stated in showed that provided the polymers having lower modulus of elasticity and tensile strength, they can be stretched upto approximately 10 times longer than its initial configuration compared to metals and ceramics. The polymers that contain small molecules of plasticisers between them are comparatively more flexible than the polymers with side chains or branch chains, since the linkages stop the molecules from sliding past each other. Tough Black PA1102, created from a renewable reserve like castor beans, is a flexible produce predominantly matched to fabrication of end use parts needing flex or which consist of living hinges, clips and latch or other closures and joints. Parts that undergo heavy use will benefit from being created using this polymeric material since the resultant part will be quite tough and will wear and tear optimally, will have resilience and unaffected to shattering or splitting.

4.3. Weight and corrosion resistance

Polymeric materials and composites such as PEEK, Polyethylene and Kynar, are invulnerable to certain severest chemicals. This increases the durability of the vehicle and avoids expensive maintenances brought about by corrosion of metal components. PEKK

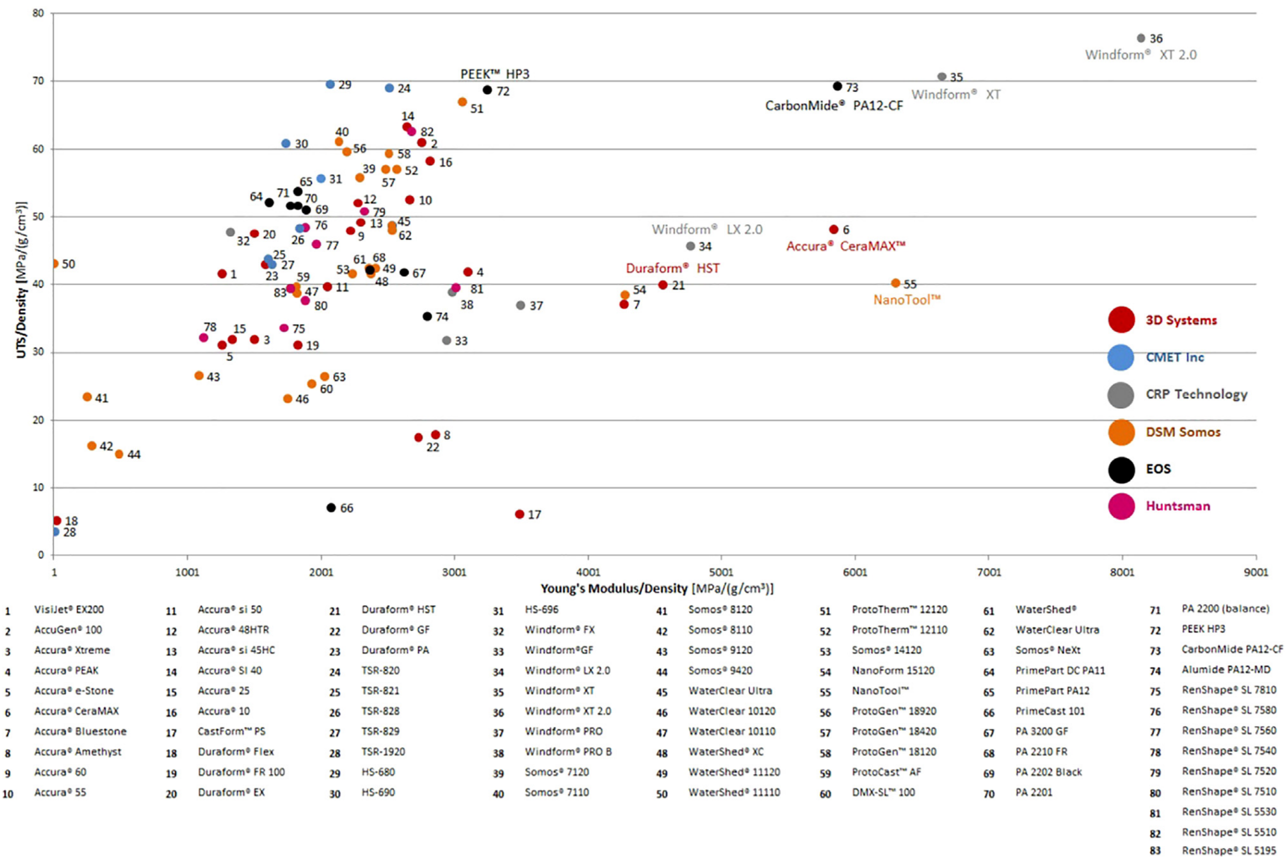

Fig. 17. Mechanical properties of most commonly used LS materials (Image Source: cirp.de).

Fig. 18. Visual appearance of few LS printed parts with different materials.

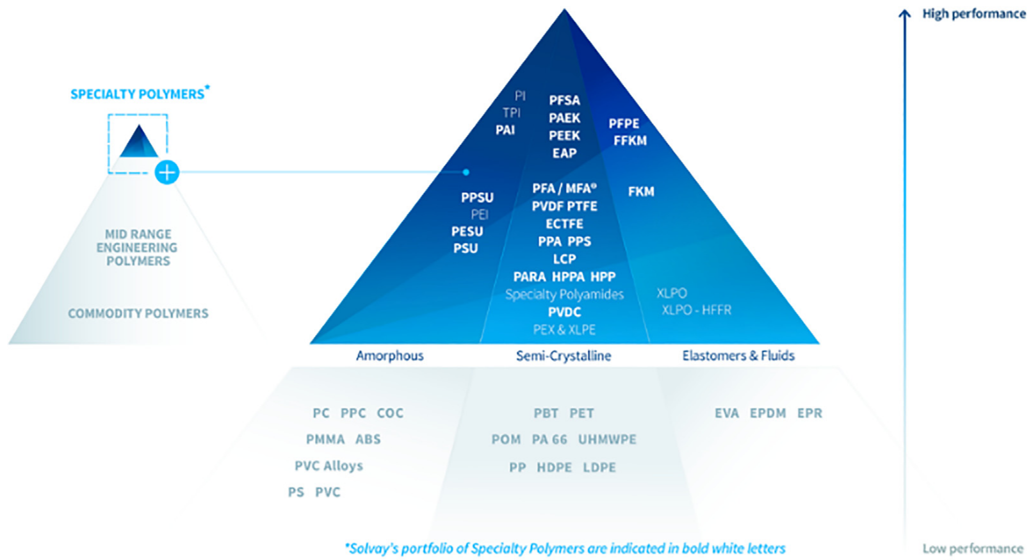

Fig. 19. High performance FDM materials from Sovey.

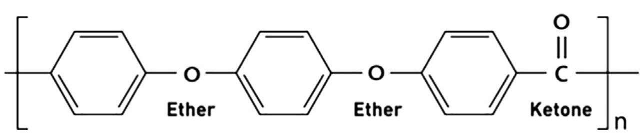

Fig. 20. Structure of pure PEEK.

material, for example, prefers acidic and alkaline surroundings, so that's where we reach when talking about the environment. Nylon 12 parts are considered stable for a long duration, offering resistance to most chemicals.

The ability to 3D print thermoplastics with greater performance characteristics like ULTEM, carbon-fibre and PEEK can conclude that metals can be swapped with plastics in some applications. Supplanting aluminium aircraft sections like brackets with choices like PEEK as suggested in the blog can affect in a range of 5% – 9% drop of weight, which can have a remarkable increase in revenue and along with that a drop in expenses on the consumption of fuel of a vehicle or an aircraft. Stratasys FDM Nylon 12CF carbon-filled thermoplastic is up towards replacing a metal machine part. 3D printing of the auxiliary part caused a component to have superior characteristics, produced much quicker than it is conventionally manufactured equivalent.

Weight of the vehicle directly affects the energy consumption of the engine and lessening in weight by 10%, actually raises the fuel economy by 7% [11]. This can simply be brought by replacing ferrous and non-ferrous metals with polymers. The specific gravities of polymeric materials compared to conventional metals have been provided in the (Table 8) below from the article.

4.4. Temperature stability

PA 2241 FR is a polyamide that has flame retarding properties for processes involving laser sintering systems. The flame retardant is halogen-based. Mainly due to its ability to be recycled, the material is highly economical, supporting low-cost part production. Typical applications include Aviation i.e. behind panel applications for example, air ducts and air outlet valves. A thermoplastic polyamide filament that is amorphous in nature, called EXTEM AMHH811F is a new material which claims great resistance to higher temperatures, appreciated by a high capacity of heat deflection up to 230° C. The material additionally has a glass transition temperature of 247 °C, which is viewed as the highest of any material that is 3D printable. Moreover, it offers extraordinary fire resistant properties, fitting chemical resistance and maintains its mechanical strength when presented to high temperatures. Graphene is one of the world's sturdiest materials as observed in [12]. Because of its high electric and heat conductivity, it is needed by various industries which extend from manufacturing a battery to aviation. A manufacturer of 3D printing fibres named Terrafilum, cooperated with XG Sciences, designer and producer of graphene nano-composites, to create graphene-upgraded materials for extrusion 3D printing. Moreover, specialists from Virginia Tech and Lawrence Livermore National Laboratory have been advancing a remarkable method to 3D print complex and convoluted items, utilizing graphene, since the year 2016. Scope of soft and stretchy IROPRINT AM materials are for footwear applications. Polymeric Materials come in three structures – tar, powder and fibre which can be utilized to make footwear, automated grippers, hoses, gaskets, seals and other elastic like applications. Among ongoing developments is 'DSM's UL Blue Card-certified' fire resistant material, Novamid AM1030 FR, for extrusion 3D printers. The material has been created from 'DSM's Novamid technology' and is specialized as V0 which implies that burning is stopped before 10 s when the sample is oriented vertically and V2, which means burning is stopped inside 30 s for a sample specimen situated vertically. The flame retarding capability of the material makes it suitable for applications in automotive and electronic segments.

5. Fashion and fabric industry

Fashion and Fabric industries are influenced by AM technology. Factors such as flexibility, strength, durability, shape memory, breathability are required in polymeric materials in order to be chosen as an application in this industry. Synthetic and Natural Polymers that are conventionally used in the textile industry include Polyamide, Polyester, Acrylic. From an Article published in 2012, it was found that the polymers used in Textile industry is not a new subject of thought. Since the commencement of Nylon in 1930, it was used in a greater portion of Industrial yarn and fabrics for instance belts, wall ropes, tyre cords and then was used domestically such as in Indian clothing, swimming wears etc.

Table 6
FDM materials under Stratasys [Image Source: Stratasys]

	FFF/FDM	SLA	SLS	MJF	Polyjet
RIGID	ABS-ESD7 ABS-M30 ABS-M30i ABSi Antero 800NA Antero 840CN03 ASA Nylon 12CF PC PC-ABS PC-ISO PPSF ULTEM™ 1010 CG resin Natural ULTEM™ 9085 CG resin ULTEM™ 9085 resin	SC 1000P Somos NeXt Somos ProtoGen 18,420 Somos WaterClear Ultra 10,122 Somos WaterShed XC 11,122	Nylon 11 EX Nylon 11 FR Nylon 12 AF Nylon 12 CF Nylon 12 FR Nylon 12 HST		Digital ABS Plus Vero (Rigid) Vero (Rigid) Multi-Color Nylon 11 EX Nylon 11 FR Nylon 12 AF Nylon 12 CF Nylon 12 FR Nylon 12 HST SC 1000P
High Strength	ULTEM™ 9085 resin PC-ABS ULTEM™ 1010 CG resin Natural PPSF Antero 800NA ULTEM™ 9085 CG resin Antero 840CN03		Nylon 12 HST Nylon 12 CF		
Flame retardent	ULTEM™ 9085 resin ULTEM™ 1010 CG resin Natural Antero 800NA ULTEM™ 9085 CG resin Antero 840CN03				Nylon 11 FR Nylon 12 FR
Bi0-Compatible	ABS-M30 PC-ISO ULTEM™ 1010 CG resin Natural				
Static Dissipative	ABS-ESD7 Antero 840CN03 Nylon 12 CF		Nylon 12 CF		
	FFF/FDM	SLA	SLS	MJF	Polyjet
Flexible			PE		Rigur Agilus 30A (Flexible) Agilus 40A (Flexible) Agilus 50A (Flexible) Agilus 60A (Flexible) Agilus 70A (Flexible) Agilus 85A (Flexible) Agilus 95A (Flexible)
UV Stability	ASA		Nylon 12 HST Nylon 12 CF		
Clear/Translucent	PC-ISO ABSi	Somos WaterClear Ultra 10,122 Somos WaterShed XC 11,122			Vero (Rigid)
Overmold					Overmold Agilus Black 30A over Verowhite Overmold Agilus Black 40A over Verowhite Overmold Agilus Black 50A over Verowhite Overmold Agilus Black 60A over Verowhite Overmold Agilus Black 70A over Verowhite Overmold Agilus Black 85A over Verowhite Overmold Agilus Black 95A over Verowhite
Toughness	Nylon 12		Nylon 12 PA Nylon 12 GF Nylon 12 AF Nylon 12 HST Flex TPE Nylon 11 EX Nylon 11 FR Nylon 12 FR Nylon 12 CF	Nylon 12-PA	
Chemical resistant	Nylon 12 ULTEM™ 1010 CG resin Natural PPSF Antero 800NA Antero 840CN03		Nylon 12 PA Nylon 12 HST Nylon 11 EX Nylon 12 CF	Nylon 12-PA	

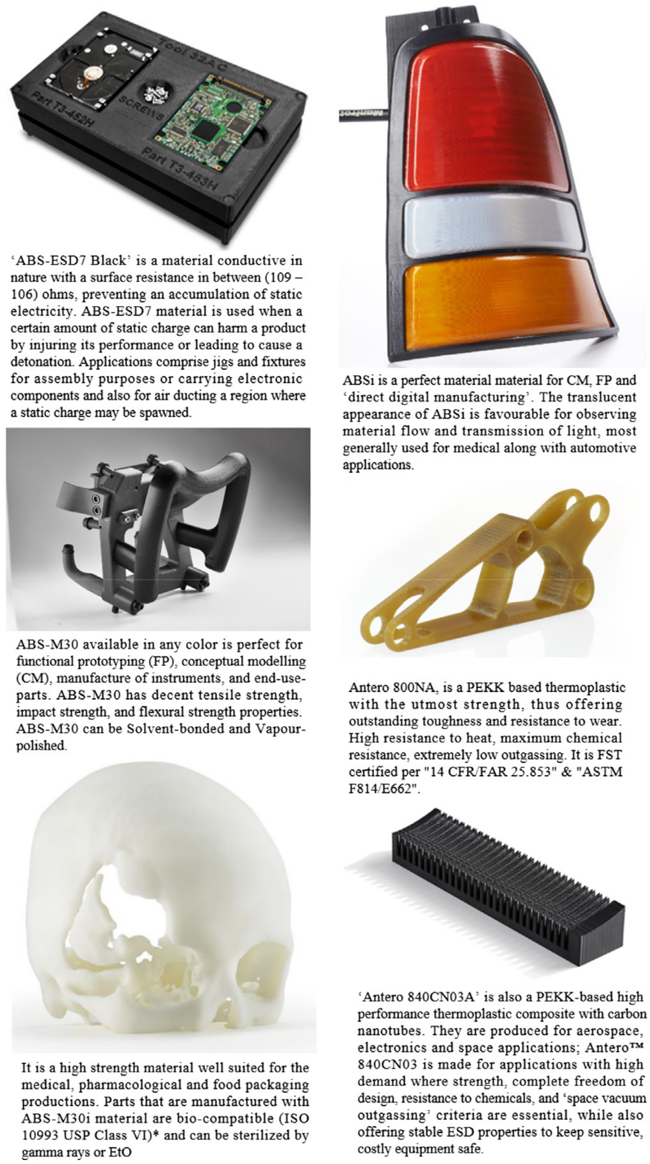

Fig. 21. Sample parts collection 1 using FDM.

Fig. 22. Sample parts collection II using FDM.

Gradually polyester was introduced in 1970 and had dominated the realm of Textile because of its own numerous encouraging properties. When polymers such as ABS, PLA, and polyamide were used, the hindrances that occurred were the increased printing time and costs, and along with that was the mechanical rigidity of plastics for AM [13].

5.1. Shape memory

Shape Memory is a property where the polymeric material tends to regain its configuration after an impact of force or external stimuli for instance thermal, mechanical, light. Shape memory is obtained by a convergence of morphology of polymer and explicit handling and can be made sense of as a polymer functionalization. By processes that fall under conventional methods and which include, injection or extrusion molding, the polymer is made into its initial, permanent shape [14]. As suggested by the Guide in, the three frequently used engineering polymers that can exhibit the shape memory effect (SME) include ethylene–vinyl acetate (EVA), polytetrafluoroethylene (PFTE), and polylactide (PLA). Certain applications include smart breathable wrinkle-free fabrics in fashion, deodorant fabrics that release fragrances at certain temperatures, skin-care products with anti-aging properties due to a regulated release of nutrients or drugs on skin [15]. It was concluded in [16] that a broadly known viable material named Nefion which is perfluorinated alkene along with short side-chains ended by sulfonate ionic group [17], exhibits a variety of shape memory behaviours that include multi-SME (Multi Shape Memory Effect) and also Temperature Memory Effect. Shape Memory Textiles are regularly founded on shape memory polymers (SMPs) first created in Japan in 1984. The stimuli that causes a shape change can be temperature, pH, light and chemical substances [18]. For thermal SMPs several factors of temperatures are necessary which include shape memory transition temperature, melting temperature, glass transition temperature. Shape memory effect has been conveyed in different categories of polymers for instance thermosets, thermoplastics, elastomers, hydrogels and liquid crystals. The

Fig. 23. Sample parts collection III using FDM.

interest for using SMPs was stimulated because of their ease in the ability to process, cost effectiveness, softness and their versatility for easy design for definite applications by different techniques such as blending, creating copolymers, adding fillers, etc. [19]. Examples of polymers which can display this shape memory effect comprise (meth) acrylates, polyurethanes, and combinations of polyurethane and polyvinylchloride.

6. Impact of using polymeric materials

Recently as a replacement for Conventional Machining process that fall under Subtractive Manufacturing, 3D printing has emerged as more economical alternative by possessing a potential to develop, produce, market and distribute different types of products [20]. According to a study conducted by Mojtaba Khorram Niaki, S. Ali Torabi, Fabio Nonino in [21] additive manufacturing possesses capabilities such as being tool-less, which inspired its utilization in rapid prototyping by 33% of the companies, 17% of companies used AM for customization that was cost effective, and 8% used it for a lower volume production. Other advantageous impacts include adoption of AM to create cost-effective complex structures that activate creativity and innovation within companies to file patents. Factors that determine the consequences of polymeric materials in additive manufacturing include the Environment, Economy, and Society. The Environmental consequences involve material demands, waste management, product life cycle, recyclable/ non-recyclability, biodegradability, emission leading to pollution and resource consumption. The Economic impacts include supply chain management, novel applications, market evolution, production costs, machinery costs, productivity. The effects on the Society consist of social benefits, labour development, product quality, public acceptance, ethics, healthcare improvements as suggested in the paper by Mehrshad Mehrpouya and Amir Dehghanghadikolaei in [22].

This section of the paper mainly focuses on the applications and impacts of using Polymers rather than any other materials such as metals and ceramics. According to the literature survey of 'Synthetic Metals' conducted in order to find a match of polymeric properties with metallic properties in [23], properties such as metallic conductivity can now be incorporated into polymers such as Polyacetylene (CH)x, which is the least complex natural polymer, can be presently be reversibly doped to the metallic system by incomplete oxidation or reduction either chemically or sometimes electrochemically. Similarly Polyaniline mentioned can be doped to the metallic system by leading a straightforward acid/ base protonation. There is indeed a long way to go for AM to be able to replace conventional machining processes, and polymers over metals. A study conducted in order to predict the future of metals [24], a survey was analysed that in an average US automobile, there was a 12% rise in the utilization of plastics and composites (up to 229 lb), and the net abatement in the utilization of steel was just 1.4% of the complete weight. The examination demonstrated that the utilization of metals in automobile parts of the industry diminished by just '0.4%', as a small amount of the vehicle weight over this equivalent period.

In AM there are Void formations between successive sheets of materials, which bring about additional porosity during the manufacturing and assembling cycle, which can diminish the mechanical performance because of a decrease in interfacial bonding between printed layers. Another basic test of AM-Anisotropic behaviour, brings about changed mechanical behaviour when exposed to vertical compression or tension, contrasted with that the horizontal way. In addition to that, transferring a Computer Aided Design (CAD) prototype into a 3D printed fragment frequently causes errors and imperfections, particularly in curved profiles and surfaces because of 'tessellation of CAD', which is an estimate of the plan of design [25].

Nonetheless, the latest research and ideas for applications of AM have been remarkable. In a new report on 'all-polymer 3D printing', SmarTech Analysis bolstered its industry-leading database of AM hardware and material sales from prior data to measure and factor in the revenues or its alike associated with polymeric 3D printed components. This resulted in a global market of $11 + billion in the year 2020, extrapolated to growing over $55 billion by the year 2030.

There is an inclination towards utilizing a superior polymer because of the requirement of having parts and models that can have exceptional dimensional, mechanical and chemical strength at incredibly high temperature and pressures even after introduction to exceptionally harsh environments for example, as exposed during in AM processes [26].

7. Conclusion

According to the study conducted in the research paper, the types of polymeric materials, their properties and their global impacts when used in additive manufacturing, have been

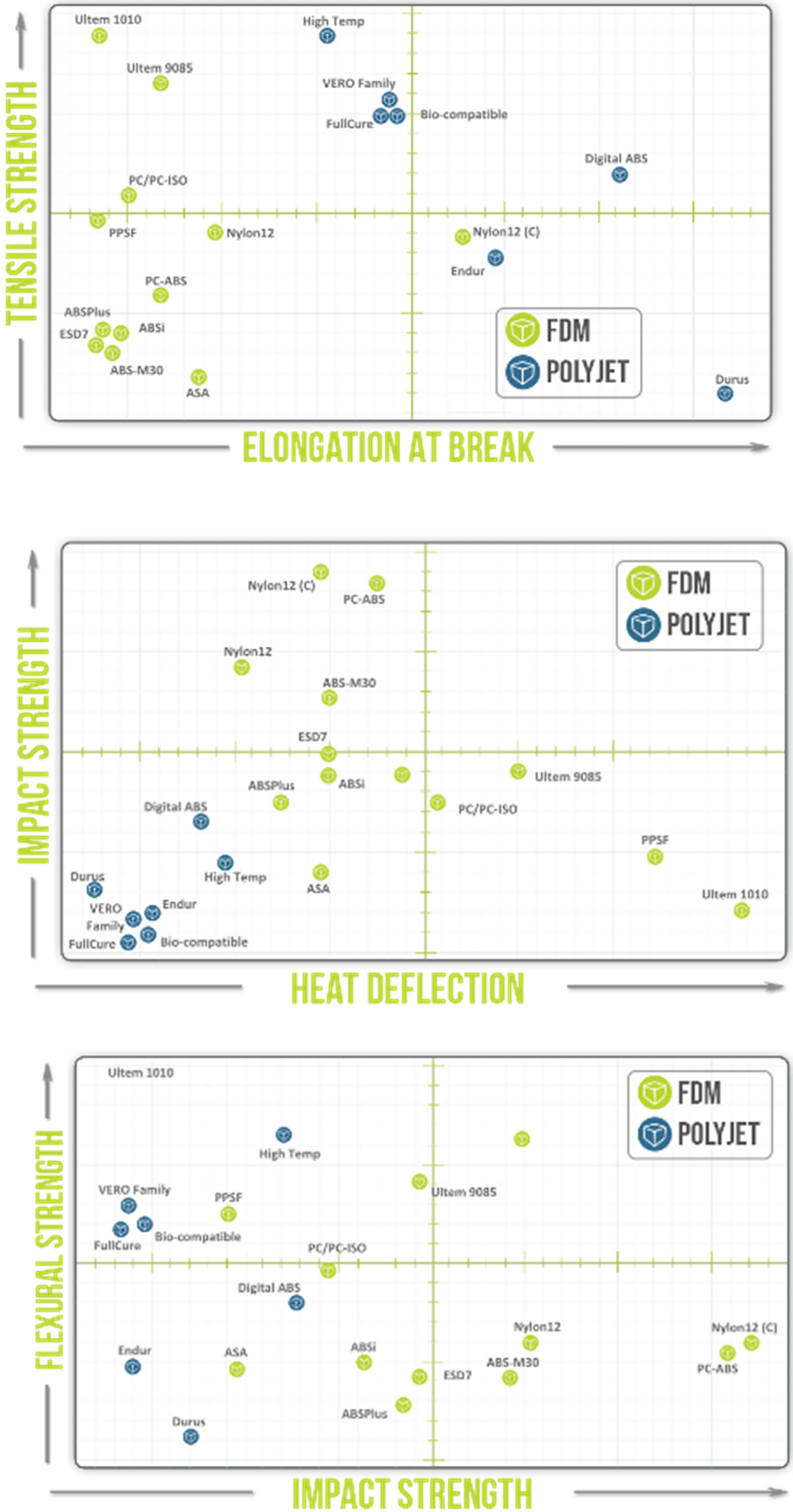

Fig. 24. Mechanical properties comparison of FDM and Polyjet 3D printing materials (Image Source: goengineer.com).

Table 7
Yield Strength (MPa), Ultimate Tensile Strength (MPa) and Elongation at break (%) of polymeric materials used in automotive industry.

Polymeric material name	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation at break (%)
Polycarbonates	58.6–70.0	50.0–75.0	10.0–138
Acrylonitrile-butadiene-styrene (ABS)	13.0–65.0	22.1–57.0	3.00–150
Polyamide (PA, Nylon 6/6, Nylon 6)	40.0–100	82.7	5–120
PVC (Polyvinyl chloride)	3.45–68.9	14.3–53.7	2–330
PP (Polypropylene)	19.0–45.0	13.8–460	8.00–750
PUR (Polyurethane)	52.4–79.3	20.7–96.0	10.0–86.0
PS (Polystyrene)	14.1–52.4	18.6–50.9	1.00–70.0
PE (Polyethylene)	2.69–200	15.2–45.0	3.00–1900
POM (Polyoxymethylene)	22.0–75.8	5.00–70.0	1.50–250
PMMA (Acrylic)	64.8–83.4	62.0–83.0	3.00–6.40
PBT (Polybutylene terephthalate)	82.7–155	20.0–186	1.00–130
PET (Polyethylene Terephthalate)	45.0–90.0	2.10–90.0	4.00–600
ASA (Acrylonitrile Styrene Acrylate)	15.0–83.4	29.4–75.5	3.00–230

Table 8
Specific Weight of polymeric materials compared to conventional metals used in automotive industry.

Polymer name	Specific weight
High impact ABS	1.03
Polycarbonates	1.19
Polyamide (PA, Nylon 6/6, Nylon 6)	1.37–1.73
PVC (Polyvinyl chloride)	1.45
PP (Polypropylene)	0.9
PUR (Polyurethane)	1.24–1.54
Metal Name	Specific Weight
Aluminium	2.55–2.80
Stainless Steel	7.7

reviewed. The paper was segregated into sections with respect to specific applications and the required mechanical and chemical properties of polymers have been determined that make it ideal for its usage. Certain properties such as Corrosion Resistance that is high in the case of PEEK can be considered for most applications requiring chemical resistance, whereas in terms of Yield Strength and Flexibility, every application requires different range of the property being exhibited by the polymer. Hence, categorizing the polymers to be the best for use cannot be concluded by direct observation, but by continuous experimentation and further research.

CRediT authorship contribution statement

J.M Jafferson: Writing - review & editing. **Debdutta Chatterjee:** Data Curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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