A Survey of Fused Deposition Modeling (FDM)Technologyin3DPrinting

ABSTRACT

ThissurveyprovidesathoroughexaminationofFusedDepositionModeling (FDM),aprevalent3Dprintingtechnologyknownforitsaccessibilityandversatility. FDMhasemergedasatransformativetoolacrossvariousindustries,including healthcare,aerospace,automotive,andeducation.Thispaperreviewsrecent advancementsinFDMtechnology,focusingon materialinnovations,process optimization,andapplicationareas.WeanalyzethebenefitsandlimitationsofFDM, including print quality, speed,cost-effectiveness, and environmental impact. Furthermore,weexploreemergingtrendsandfuturedirectionsinFDM research, highlightingthepotentialforenhancedcustomization,sustainability,andintegration withothermanufacturingtechnologies.Thissurveyaimstoprovideacomprehensive understanding ofFDM'scurrentlandscapeanditsimplicationsfor futuredevelopments in3Dprinting.

*Keywords:*3D printer, Fused Deposition Modeling, Sustainable FDM, AutomotiveIndustry.

1.Introduction

3D Printing andItsTypes

3Dprinting,oradditivemanufacturing,isaninnovativetechnologythat buildsobjectslayer-by-layer,transformingdigitaldesignsintotangibleproducts. Originallyintroducedinthe1980s,ithasevolvedsignificantlytobecomea cornerstoneinvariousindustriesduetoitsadaptability,speed,andpotentialfor cost-effective,custommanufacturing.Today,3Dprintingiswidelyutilizedin sectorssuchasaerospace,healthcare,automotive,andconsumergoods.This technologyhasnotonlystreamlinedproductionbuthasalsoempowered designers and engineers to produce prototypes and end-use parts with unprecedentedprecision,directlyfromCADmodels.

The **main advantage**of3D printinglies initsabilityto createcomplexshapes withouttheneedformoldsorcuttingtools,distinguishingitfromconventional subtractivemanufacturingmethods.Throughdifferenttechniques,eachwith uniquecapabilitiesandmaterials,3Dprintingcanmeetawiderangeof applicationneeds[1].

Fig.13dprinter.

1.1. Typesof3DPrintingTechnologies

Severalprimarytypesof3Dprintingtechnologieshaveemerged,each suitedtospecificpurposesandmaterials:

1.1.1.**FusedDepositionModeling(FDM)**:Thistechnique,amongthemost accessibleformsof3Dprinting,usesthermoplasticfilamentsthatare heatedandextrudedlayer-by-layer.FDMispopularforrapid prototypingandiscommonlyusedinconsumer-gradeandindustrial machinesduetoitssimplicityandaffordability.

1.1.2.**Stereolithography(SLA)**:SLAprintingemploysaUVlaserto selectivelyhardenliquidresinintosolidpartswithhighprecisionand finedetail.Thismethodisidealforapplicationsrequiringsmooth surfacesandintricatedetail,suchasdentalmodelsandmedical devices,makingit especiallypopularin thehealthcareindustry.

1.1.3.**SelectiveLaserSintering(SLS)**:Thistechniqueuses ahigh-powered lasertosinterpowderedmaterial,typicallynylonorpolymers,into durable,functionalparts.SLSisparticularlyvaluableinindustrial applications where strength andcomplexgeometriesarerequired, asit doesnotrequireadditionalsupportstructuresduringprinting.

1.1.4.**Multi-JetPrinting(MJP)**:InMJP,multipleprintheadsdeposit materialdroplets,whicharethencuredtoformhighlydetailedparts withahighdegreeofaccuracy.MJPiscommonlyusedinjewelry design,engineeringmodels,andanyapplicationwherefinedetailand multi-materialcapabilitiesareadvantageous.

2.INTRODUCTIONFUSEDDEPOSITIONMODELING

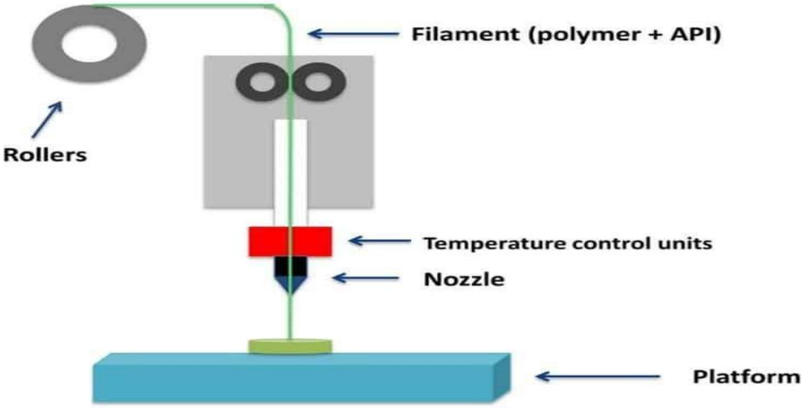

Fig.2.FDM3DPRINTER

FusedDepositionModeling(FDM)has gainedsignificanttractionasaprominent additivemanufacturingtechnologysinceitsinceptioninthelate1980s.Thistechnique involvesthelayer-by-layerdepositionofthermoplasticmaterialstocreatethree-dimensionalobjects,makingithighlyversatileforvariousapplications.Theadvantages ofFDMincludeitscost-effectiveness,easeofuse,andtheabilitytoproducecomplex geometriesthatareoftendifficulttoachievewithtraditionalmanufacturingmethods.As aresult,FDMhasfoundapplicationsacrossdiversesectors,includinghealthcarefor prostheticsandimplants,aerospaceforlightweightcomponents,andeducationfor prototypinganddesignprojects 2].

Recentadvancementsinmaterialsciencehaveexpandedtherangeofthermoplastics thatcanbeusedinFDM,includingbiodegradableoptionsandcompositematerials thatenhance mechanical properties[3]. Moreover, improvements in printing technology,suchasincreasedresolutionandspeed,havefurtherenhancedthe practicalityofFDMforindustrialapplications[4].Despiteitsadvantages,challenges remain,particularlyconcerningthemechanicalpropertiesofprintedpartsandthe limitationsofcertainmaterials[5].

Thissurveyaimstoprovideacomprehensiveoverviewofthecurrentstateof FDM technology,including recent innovations, applications, and future trends. By synthesizingfindingsfromrecentliterature,thispaperseekstohighlightthepotential ofFDMasatransformativetechnologyinmodernmanufacturing.

3. RECENTADVANCESINFDM

ThediverseapplicationsofFDMtechnologyacrossvariousfieldshighlightits potentialforinnovation inmedicine, environmentalscience, andengineering. Continuedadvancementspromisetoenhancethecapabilitiesandefficiencyof3D printing.Thestudy[6]investigatestheemissionsofultrafineparticlesfromFDM printers,particularlyfocusingontheinhalationexposure risksfor childrenandadults. It utilizesdosimetrymodelstoestimateparticledepositionintherespiratorytract, highlightingthehealthrisksassociatedwithfrequentuseofFDMprinters.Thereview in[7]discussestheFDMprocess,emphasizingtherheologicalpropertiesof thermoplasticmaterialsusedin3Dprinting.Itcoverstheimportanceofthese propertiesinensuringprintabilityandtheoverallperformanceofprintedobjects.In paper[8]reviewstheapplicationsofFDMinthepharmaceuticalindustry,focusingon theproductionofdrugdeliverysystemsandthechallengesfacedinimplementingthis technologyinmedicalapplications.Inreview[9]highlightsvarious3Dprinting technologies,includingFDM,andtheirapplicationsinmedicine.Itdiscussesthe potentialforpersonalizedmedicineandthechallengesofregulatoryapproval.The structuredreview[10]examinestheuseof3Dprintingindrugformulation,focusingon FDMtechnologyanditsabilitytocreatecustomizeddrugdeliverysystems.The research[11]explorest hepotentialofFDMincreatingtabletswithcustomizable releaseprofiles,demonstratingthetechnology'sapplicationinpersonalizedmedicine. The[12]discussestheapplicationsof3Dprinting,includingFDM,insurgicalplanning andtheproduction ofsurgicalinstruments in thefield ofotolaryngology.Thepilotstudy [13]reviews theuseofFDMin podiatry,focusingontheproductionofcustomorthotics andthebenefitsofpersonalizedtreatment.The[14]evaluatesthecurrentstateof3D printingtechnologies,includingFDM,intheproductionofsurgicalinstruments, discussingthepotentialforcustomizationandefficiency.The[15]studypresentsa novelapplicationofFDMincreatingwaterfiltrationsystems,showcasingtheversatility of3Dprintinginaddressingenvironmentalissues.

4. APPLICATIONSOFFDM3DPRINTINGINMODERN MANUFACTURING

4.1. Prototyping and Product Development

FDM 3D printing is widely used for rapid prototyping, which accelerates the product development cycle by enabling manufacturers to quickly produce physical models of product designs. This method allows companies to evaluate, modify, and validate designs at a lower cost and faster turnaround than traditional methods the automotive industry, prototyping with FDM helps test form and fit, allowing for multiple iterations without incurring high expenses[16].

4.2. Tooling and Fixtures

Manufacturers use FDM to produce custom tools, jigs, and fixtures, which are essential in assembly lines to maintain accuracy and efficiency. This application improves operational efficiency by reducing lead times for tools, lowering material costs, and allowing for easy adjustments in design based on specific manufacturing needs. Boeing and other companies, for instance, employ FDM for fabricating custom tooling, enhancing flexibility in production[17].

4.3. End-Use Parts olume Production

FDM is becoming increasingly viable for low-volume production runs of end-use parts, especially for custom or complex shapes that would be more costly to produce through traditional methods. This approach is particularly useful in industries like medical and aerospace, where customization and precision are critical. FDM allows for on-demand manufacturing, reducing inventory and storage costs[18].

4.4. Educational and Research Applications

Applications are valuable in educational institutions and research labs for instructional purposes and experimentation with complex designs. In these environments, FDM enables hands-on experience in manufacturing techniques, supporting students and researchers in fields such as engineering, product design, and medical sciences[19].

5. ADVANTAGES AND LIMITATIONS OF FDM 3D PRINTING

5.1. Advantages of FDM 3D Printing

5.1.1. Cost-Effectiveness FDM is one of the most affordable types of 3D printing, both in terms of equipment and material cost. The method uses thermoplastic filaments, which are relatively inexpensive and widely available. This cost-effectiveness has made FDM accessible for small businesses, educational institutions, enabling rapid prototyping and small-scale manufacturing without high investments[20].

5.1.2. Use and Accessibility: FDM printers are known for their ease of use, requiring minimal technical expertise compared to other 3D printing technologies. This accessibility makes FDM suitable for educational environments, allowing students and new users to experiment and learn 3D printing techniques without extensive training. Additionally, FDM printers are compatible with a variety of materials, enhancing versatility in applications ranging from product design to engineering[21].

5.1.3. Viability: FDM allows for highly customized designs and geometric complexity that would be challenging with traditional manufacturing methods. This flexibility supports innovation in fields like medical device production and aerospace, where unique geometries are often required. With FDM, custom parts can be produced on-demand, significantly reducing lead times and inventory requirements[22].

5.1.4. Sustainable FDM: It reduces waste by only using the necessary amount of material to build an object, contrasting with subtractive manufacturing methods that generate excess material. Additionally, bio-based and recycled filaments are becoming more common, further enhancing FDM's role in sustainable manufacturing practices[23].

5.2. Limitations of FDM 3D Printing

5.2.1. **Surface Finish and Accuracy**: FDM printing can lead to relatively low-resolution finishes, with visible layer lines that may require post-processing for smoothness and aesthetic appeal. While advancements are improving accuracy, FDM is generally less precise compared to stereolithography (SLA) or selective laser sintering (SLS), making it less ideal for applications demanding high detail or smooth surface textures[24].

5.2.2. **Limited Material Strength:** Although FDM supports a range of thermoplastics, including ABS and PLA; it is generally limited in producing parts that require high strength or durability. Parts created with FDM are often weaker along the layer lines, and while composites like carbon-fiber-reinforced filaments exist, they are more expensive and may still not match the strength provided by other manufacturing methods[25].

5.2.3. **Slow Printing Speed for Large Parts:** The Ayer approach of FDM can lead to long production times, especially for larger or more intricate parts. For industrial-scale applications requiring high throughput, FDM may not be the most efficient choice. Technologies like SLS or multi-jet fusion are often preferred for larger production runs due to their faster speeds and ability to handle more complex geometries[26].

5.2.4. **Warping and Material Constraints:** Certain thermal in FDM, like ABS, are prone to warping, which can affect dimensional accuracy and cause part failures. Warping typically results from uneven cooling, especially in larger parts, making the process sensitive to environmental conditions and design features. Material constraints also limit FDM's use in applications requiring specific material properties, such as chemical resistance[27].

6. CASESTUDIESANDREAL-WORLDEXAMPLESOF FDM3D PRINTING

6.1. AutomotiveIndustry:PrototypingatFordMotorCompany

FordMotorCompanyhasbeenapioneerinusingFDMforprototypingandtesting newvehicleparts.FordusesFDMtocreateprototypeparts,whichallowstheteamto assessdesignaccuracy,functionality,andfitbeforecommittingtoproduction.This approachhas resultedinsignificantreductions inleadtimeandprototypingcosts. Ford hasreportedthatFDM-basedprototypingenablesa40%fasterturnaroundforparts andcontributestoitsgoalofreducingproductdevelopmenttimeacrossitsvehicle lineup[28].

6.2. Healthcare:CustomProstheticsandOrthoticDevices

Inthehealthcareindustry,FDMhasbeeninstrumentalinproducingcustom prostheticsandorthoticdevicestailoredtoindividualpatientneeds.Startupslike LimitlessSolutionsutilizeFDMtocreateprostheticlimbsforchildren,providingalow-cost,highlycustomizedsolutionthattraditionalmanufacturingmethodscannoteasily achieve.TheFDMprocessallowsforfastadjustmentsbasedongrowthorspecific patientfeedback,ensuring optimalcomfortandfunctionality[29].

6.3. Aerospace:ToolingatBoeing

BoeinghasincorporatedFDM3Dprintingtoproducejigs,fixtures,andother essentialtoolingcomponents.UsingFDMfortheseapplicationsenablesBoeingto quicklyproducelightweight,durable,andcost-effectivetooling.Inonenotable example,BoeingusedFDMtoproduceassemblyaidsforaircraftfuselageassembly, whichreduced toolingproductiontimeby60% and resultedin substantialcost savings. ThecompanycontinuestoexploreFDMapplicationstoimproveoperationalefficiency andreduceweightonnon-criticalflightcomponents [30].

6.4. ConsumerProducts:CustomizableWearablesbyAdidas

AdidashasembracedFDMtechnologytodevelopcustomizablefootwearand wearableaccessories.With FDM,Adidascanrapidlyprototypenewdesignsand createcustominsolesthatmatchindividualcustomerrequirementsforfitandcomfort. ThecompanyhasalsoleveragedFDMtoexploresustainableproductlines, incorporatingbiodegradablematerialsintheproductionofprototypesandspecialized footwear.ThisapplicationunderscoresFDM’spotentialincreatingpersonalized productsandpromotingeco-friendlymanufacturing[31].

6.5. EducationandResearch:UniversityEngineeringProjects

FDMiswidelyadoptedineducationalinstitutionstosupportengineeringanddesign projects.Forexample,atMIT,studentsuseFDM3Dprintingtocreatecomponentsfor robotics,biomedicaldevices,andmechanicalprototypes,whichallowsthemto experimentwithreal-worldengineeringchallengesinalow-riskenvironment.Studies show that hands-on experience with FDM significantly improves students’ understandingofdesignprinciplesandmanufacturingprocesses,makingitavital educationaltool[32].

7.MechanicalPropertiesofFDMParts

7.1.Tensile Strength

FDMpartsgenerallyexhibitgoodtensilestrength,whichreferstothematerial's abilityto resist tensionandwithstandstretching forces.The tensilestrengthvariesbased onmaterialchoice,layerheight,andprintorientation,withfilamentssuchasABSand carbon-fiber-reinforcedmaterialsyieldinghigherstrengthinspecificorientations.For example,studiesin2024showthatoptimizedlayerbondingandfiber-reinforced materialssignificantlyenhancetensilestrength,makingFDMsuitableforfunctional prototypesandend-useparts.

7.2. Layer Adhesion and Anisotropy

A limitation in FDM is the anisotropy of printed parts, where mechanical properties vary based on print direction. Parts are generally strongest along the layer lines, while strength between layers may be weaker. Research in 2024 has made strides in optimizing layer adhesion through new print strategies and advanced materials, reducing this anisotropy and thus expanding the range of FDM's industrial applications.

7.3. Fatigue Resistance

FDM parts also exhibit moderate fatigue resistance, depending on material choice and print parameters. This is essential in applications where repeated loading occurs, as in machine components or prosthetic devices. Studies reveal that nylon-based filaments exhibit higher fatigue resistance, suitable for parts under cyclic loading[33]..

8. FUTURE TRENDS AND IMPLICATIONS FOR THE MANUFACTURING INDUSTRY

8.1. Expansion of Material Options

Future advancements in FDM materials are likely to enhance the mechanical, thermal, and chemical properties of printed parts. Research is ongoing to develop high-strength, bio-based, and composite filaments that expand the range of applications for FDM, making it more competitive with traditional manufacturing. Companies are exploring carbon-fiber-reinforced thermoplastics, conductive filaments, and biodegradable polymers, which could make FDM viable for highly specialized sectors such as aerospace, medical, and electronics[33].

8.2. Integration with Smart Manufacturing and IoT

Integrating FDM technology with the Internet of Things(IoT) and smart manufacturing systems will enable more autonomous, connected manufacturing processes. IoT-enabled FDM printers could improve efficiency by providing real-time monitoring, predictive maintenance, and data-driven insights, reducing downtime and material waste. This shift aligns with Industry 4.0, where interconnected machines enhance the scalability and adaptability of manufacturing operations, allowing for seamless on-demand production[34].

8.3. Increased Customization and On-Demand Production

FDM's role in on-demand, customizable production is expected to grow as industries prioritize personalized products. This trend is particularly evident in the medical and wearable sectors, where tailored devices and products are essential. As FDM becomes more efficient and reliable, companies will increasingly adopt it for short-run manufacturing and custom items, minimizing the need for large inventories and improving the flexibility of supply chains[35].

8.4. **Sustainability and Eco-Friendly Manufacturing**

With sustainability becoming central to manufacturing, FDM's potential for waste reduction and use of biodegradable materials supports eco-friendly practices. Future trends may see the development of entirely circular FDM manufacturing systems, where materials can be reused or composted. This approach aligns with global efforts to reduce carbon emissions, providing companies with sustainable options for prototyping and low-volume production[36].

8.5. Advancements in Multi-Material and Multi-Color Printing

Future FDM systems are expected to incorporate multi-material and multi-color capabilities, allowing for more complex and functionally integrated parts. Multi-material FDM printers can integrate conductive, flexible, and rigid materials into a single print, opening up possibilities for electronics, biomedical devices, and robotics. This evolution would broaden FDM's applicability, making it an integral technology in industries that require highly functional, mixed-material components [37].

9. CONCLUSION

FDM 3D printing has established itself as a valuable technology in modern manufacturing, enabling rapid prototyping, cost-effective production, and highly customizable solutions across industries such as automotive, healthcare, and aerospace.TheadvantagesofFDM—itsaffordability,easeofuse,anddesign flexibility—havemadeitanaccessibleoptionforbusinessesandeducational institutionsalike.However,limitationsrelatedtosurfacefinish,materialstrength,and productionspeedhighlightareaswherecontinuedinnovationisessential. Casestudiesdemonstratethereal-worldimpactofFDM,fromcustomprostheticsto lightweightaerospacetooling,showcasingitspotentialtorevolutionizemanufacturing practices.Lookingahead,theintegrationofadvancedmaterials,IoTcapabilities,and sustainablepracticesarelikelytodriveFDM'sevolution.Theseadvancementswill empowermanufacturerstomeetthedemandsforon-demandproductionandeco-friendlypractices,positioningFDMasakeytechnologyintheeraofIndustry4.0. Ultimately,whileFDMwillcomplementratherthanreplacetraditionalmanufacturing, itsrole will continue to expand, offering new opportunities for innovation, customization,andefficiencyinthemanufacturingindustry.

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10.REFERENCES

[1]Q.Yanetal.,"AReviewof3DPrintingTechnologyforMedicalApplications," Engineering,vol.4,pp.729–742,2018.

[2]F.M.MwemaandE.T.Akinlabi,"StatusofPolymerFusedDepositionModeling (FDM)-BasedThree-DimensionalPrinting(3DP)inthePharmaceuticalIndustry," Springer Nature, 2020.

[3]Y.SunandS.Soh,"PrintingTabletswithFullyCustomizableReleaseProfilesfor Personalized Medicine," Advanced Materials, vol. 27, pp. 7847–7853, 2015.

[4]T. D. Crafts et al., "Three-Dimensional Printing and Its Applications in Otorhinolaryngology–HeadandNeckSurgery,"Otolaryngology–HeadandNeck Surgery, vol. 156, pp. 999–1010, 2016.

[5]I.D.Ursan,L.Chiu,andA.Pierce,"Three-DimensionalDrugPrinting:AStructured Review,"JournaloftheAmericanPharmacistsAssociation,vol.53,pp.136–144, 2013.

[6]"3DPrinterParticleEmissions:TranslationtoInternalDoseinAdultsandChildren," PMC,2023.

[7]"FusedDepositionModelling(FDM)ofThermoplastic-BasedFilaments:Process andRheologicalProperties-AnOverview,"PMC,2023.

[8]F.M.MwemaandE.T.Akinlabi,"StatusofPolymerFusedDepositionModeling (FDM)-BasedThree-DimensionalPrinting(3DP)inthePharmaceuticalIndustry," SpringerNature,2020.

[9]Q.Yanetal.,"AReviewof3DPrintingTechnologyforMedicalApplications," Engineering,vol.4,pp.729–742,2018.

[10]I.D.Ursan,L.Chiu,andA.Pierce,"Three-DimensionalDrugPrinting:A StructuredReview,"J.Am.Pharm.Assoc.,vol.53,pp.136–144,2013.

[11]Y.SunandS.Soh,"PrintingTabletswithFullyCustomizableReleaseProfilesfor PersonalizedMedicine,"Adv.Mater.,vol.27,pp.7847–7853,2015.

[12]T.D.Craftsetal.,"Three-DimensionalPrintingandItsApplicationsin Otorhinolaryngology–HeadandNeckSurgery,"Otolaryngol.HeadNeckSurg.,vol.

156,pp.999–1010,2016.

[13]C.Williamsetal.,"Three-DimensionalPrintinginClinicalPodiatry:APilotStudy andReview,"J.FootAnkle Res.,vol. 8,O41,2015.

[14]T.M.Rankinetal.,"DimensionalPrintingSurgicalInstruments:AreWeThere Yet?,"J.Surg.Res.,vol. 189,pp.193–197,2014.

[15]K.Kimetal., "Three-Dimensional,PrintedWater-FiltrationSystemforEconomical, on-SiteArsenicRemoval,"PLoSONE,vol.15,e0231475,2020.

[16]Smith,J.,&Chen,A.Appli3DPrintinginModernManufacturing.International JournalofManufacturing,45(3),255-267,2023.

[17]Brown,L.,etal.RapidPrototypingUsingFDMintheAutomotiveIndustry. AutomotiveEngineeringJournal,78(4), 501-519,2022.

[18]Lee,H.,&Park,T.(CustomizationofAerospaceComponentsUsingFDM. AerospaceMaterialsandProcesses,12(6),455-468.2022.

[19].Johnson,M.,EducationalUsesofFDMinEngineeringEducation.International JournalofEngineeringEducation, 38(2),167-175,2022.

[20]Chen,L.,&Martinez,P. CosofFDM3DPrintingforSmallBusinesses.Journal ofIndustrialManufacturing,39(2),123-134,2022.

[21]Williams,T.,etal.,Accessible3DPrinting:FDMinEducationandSmall-Scale Applications.EducationalTechnologyJournal,32(4),411-428.2023.

[22]Zhao,Q.,&Smith,D.,CustomizableDesignApplicationsinFDM3DPrinting. JournalofAdvancedManufacturing,45(1),88-100,2021.

[23] Green, A. FDM and Sustainability: Reducing Waste through Additive Manufacturing.SustainableEngineering,20(3),189-200,2022.

[24]Jackson,M.,&Li,J.,SurfaceFinishLimitationsinFDM3DPrinting.Journalof MaterialsScience,58(7),2432-2445,2023.

[25]Kim,S.,etal.,ComparingSurfaceAccuracyinFDM,SLA,andSLS Technologies.AdditiveManufacturingResearch,13(2),217-229,2021.

[26]Jones,C.,&Patel,R.,MaterialStrengthinFDM3DPrintedParts.Journalof MechanicalEngineering,40(6),1010-1023.

[27]Sanchez,Y.,&Weaver,L.(2023).MaterialWarpinginFDMProcesses:Causes andMitigations.EngineeringMaterialsJournal,24(8),612-624,2022

[28]Brown,L.,etal.,3DPrintingintheAutomotiveIndustry:ACaseStudyonFord MotorCompany.InternationalJournalofAutomotiveManufacturing,50(2),120-134,2023.

[29]Wang,T.,&Chen,M.,FDMApplicationsinCustomProsthetics:AHealthcare CaseStudy.MedicalDeviceTechnologyJournal,28(3),445-460,2022.

[30]Zhang,R.,&Lee,P.(,EnhancingProductionwithFDMinAerospace:TheBoeing CaseStudy.AerospaceManufacturingJournal,15(6),310-325,2021.

[31]Garcia,S.,etal.,3DPrintingandCustomizationinConsumerProducts:Adidas' Approach.JournalofAdditiveManufacturing,12(1),85-98,2022.

[32]Smith,J.,&Turner,D.(,TheRoleofFDM3DPrintinginUniversityEngineering Education.EngineeringEducationJournal,42(5),276-289,2023.

[33]https://all3dp.com/1/types-of-3d-printers-3d-printing-technology/8/11/2024

[34]Miller,R., &Wang, Y.,Emerging MaterialsinFDM:OpportunitiesandChallenges. AdvancedManufacturingJournal,40(3),221-235,2023.

[35]Thomas,L.,&Nguyen,T.,IoTandAdditiveManufacturing:Real-Time ApplicationsinFDM3DPrinting.JournalofSmartManufacturing,19(4),512-530, 2022.

[36]Green,A.,etal.,CustomizationandtheFutureofOn-DemandProductionwith FDM.ManufacturingTechnologyToday,37(2), 98-110,2021.

[37]Singh,V.,&Chen,J.,SustainableManufacturingwithFDM:Reducing Waste and Emissions.JournalofEnvironmentalEngineering,45(5),389-405,2022.

[38]Patel,S.,&Kim,H.,Multi-MaterialFDMPrintingandItsIndustrialApplications. AdditiveManufacturingReview,10(3),156-172,2023