Mechanical properties of parts fabricated with additive manufacturing: A review of mechanical properties of fused filament fabrication parts

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Abstract: *Additive Manufacturing (AM) Technologies are in constant development since their emergence in the late 80s. However, standardization is still in its infancy, owing to the numerous changing variables in each process. One of the most common are the material extrusion process, in which thermoplastic is extruded, also known as fused filament fabrication (FFF). The popularity of this process is due to the relatively simple method as well as the relatively good mechanical properties of the fabricated parts. There are numerous research studies evaluating mechanical properties because the FFF process allows for the investigation of many variables and the production of many parts with a wide range of characteristics. But how good are those characteristics in reality, and how good do we need them to be? It all depends on the application for which those parts are required.*

Keywords: *MECHANICAL PROPERTIES, FABRICATION, FUSED FILAMENT FABRICATION (FFF), ADDITIVE MANUFACTURING (AM)*

1. Introduction

Additive Manufacturing (AM) technologies are group of processes that build physical model using a three-dimensional Computer-Aided Design (3D CAD), without the need of process planning [1]. Fused filament fabrication (FFF) is an AM process in which the material (most often: thermoplastic) is being extruded though heated nozzle. It is also known under the name fused deposition modeling (FDM), term that is patented by Stratasys. FFF works in the same working manner as all the AM technologies, by building the model layer by layer. This offers many advantages such as geometry complexity, lattice structures, diversify small series and personalized parts fabrication. At the same time, the unique working manner creates challenges for the designers and engineers. One of those challenges are the mechanical properties of the fabricated parts. Mechanical properties of the parts fabricated via FFF differ from the properties of the injection molding parts, even when made from the same material. Determining the cause that influence on the mechanical properties is complex task since it involves many variables, such as: working conditions, process parameters, the material and the machine.

2. Methodology

Determining the mechanical properties of the fabricated parts and what influence the most on them are the concerns for this study. In order to have systematic analysis, two research questions are set: Q1. Which process parameters are taken into consideration for mechanical properties?; Q2. What are the outcomes and findings of these studies and how can they be used in further research?.

In the reviewing process papers from relevant journals and conferences from 1998 to 2022 year were taken into consideration. Papers regarding the mechanical properties of parts fabricated with commercial and open-source FFF machines are analyzed.

3. Analysis

In the text below brief overview of the analyzed paper is given, while in Table 1 detail classification is presented. Bertoldi et al. [2] observed the connection between the mechanical properties and the part orientation. According to their study, the highest values for the modulus of elasticity and the maximum tensile stress were obtained for specimens placed in the y-z plane. The specimens made in the x-z plane have the lowest value for the maximum tensile stress. A critical position is the vertical placement of the test tube (x-z), due to the high number of layers (> 600), which causes brittle failure. Bellini and Güçeri [3] conducted a similar research with identical results. The samples placed in XZY show the highest values for ultimate tensile stress of 15.99 MPa and Young's modulus of 1653 MPa. While the specimens placed in ZXY show the lowest values for ultimate tensile stress of 7.608 MPa and Young's modulus of 1391 MPa. Ahn [4] takes into consideration the raster width (RW), but report that it has no particular impact on the mechanical properties of the part. Regarding the orientation of the part in the build chamber, the same results are reached by Hussein et al. [5] analyzing pieces of PC (polycarbonate). The highest values for the maximum tensile strength were achieved for the specimens placed in the XZY position, and the lowest for those placed in the ZXY position. In their research, Sood et al. [6] analyze the influence of the part positioning and orientation on the build plate. According to them, the maximum tensile strength and the maximum bending strength decrease with an increase in the angle with respect to the build plate. In later research, Sood et al. [7] investigate the influence of the process parameters on the compressive strength of the parts fabricated with FDM. It is concluded that a maximum compressive strength value of 17.4751 MPa is achieved at the following process parameters: layer thickness 0.254 mm, position 0.036°, screen angle 59.44°, screen thickness 0.422 mm and screen gap 0.00026 mm. Lee et al. [8] analyze the influence of the part positioning and orientation on compressive strength. According to the results, the compressive strength is 11.6% higher when the piece is placed axially than when placed transversely on the build plate. Uddin et al. [9] conduct research in exploring the influence of key printing parameters on mechanical properties of ABS (Acrylonitrile butadiene styrene) specimens. Three parameters were taken into consideration: layer thickness (0.09 mm, 0.19 mm, and 0.39 mm); build plane (XY, YZ, and ZX); and printing orientation (horizontal, diagonal, and vertical). Highest Young's modulus of 1524MPa is noted on specimens with layer thickness of 0.09mm and YZ-H orientation. However, the highest yield strength of 39 MPa is noted in specimens with layer thickness of 0.09mm and YZ-H and YZ-D orientation. In this research it is concluded that the build plane orientation does not have high effect on compressive properties. Slonov et al [10] analyzed the influence of the process parameters on the mechanical properties of PPSU (polyphenylene sulfone) parts. They found out that the best mechanical properties are obtained under the conditions of longitudinal orientation of filaments with a minimum width and negative air gaps between them.

Es-Said et al. [11] investigate the influence of the layer orientation on the mechanical properties. The conclusion is that in the case when the piece is placed horizontally on the bed (0° orientation), with the layers being longitudinal, superior strength and impact resistance is achieved compared to all other positions.

This is also confirmed by other research [12, 13]. Specimens placed along the x axis at an angle of 0° have good maximum bending strength, while specimens placed along the y axis at an angle of 0° have good maximum tensile strength [12]. According to their results, the specimens made along the z axis have significantly the worst results with the highest value of 22.51 MPa for the elongation at a position of 45° in relation to the axis. When it comes to anisotropic features, they are most likely caused by the way the layers are joined [11]. Onwubolu and Rayegani [13] analyze the process parameters (layer thickness, position, raster angle (RA), RW, air gap) to see their influence on the maximum tensile strength. An improvement in the maximum tensile strength is achieved with a minimum layer thickness, minimum RW, a larger RA and a negative air gap [13].

Ahn et al. [4] conducted an investigation on the maximum tensile strength by varying the RA and RW as well as the perimeter to the raster beam. Their research shows that the RA has an effect on the maximum tensile strength, but at a constant RA of 0° and an angle beam perimeter of -76.2 µm, the tensile strength increases by about 30%. The RA has no influence on the tensile strength. Similar results have been reached by Sood and colleagues [14]. In this research, it was concluded that at a positive value for the air gap, the material "flows" between the adjacent layers, which leads to an increased contact area between the layers, and this leads to an increase in the maximum tensile strength of about 15% for thinner layers, for example 0.127 mm.

Shubham [15] came to a conclusion that the layer thickness has influence on the mechanical properties. By increasing the layer thickness, the maximum tensile strength decreases by 46%, the impact force by 54.5% and the flexural strength by 40%. The only exception are the specimens with layer thickness of 0.5 mm, which show deviations in the mechanical properties [15]. This research is followed up by Masood [16] and Hossain [5], considering PC parts. According to Masood [16] the highest value for the maximum tensile strength of 58.8 MPa was achieved at a grid angle of 45°/-45° and a layer thickness of 0.60064 mm. But according to this research, no general rule can be adopted for the maximum tensile stress in relation to the angle of the grid and the layer thickness. Hossain [5] take into account the position, in addition to the RA, RW, air gap and the contour width (CW).

Syamsuzzaman et al. [17] compared the mechanical properties (tensile and compressive properties) of a specimens fabricated on commercial and open-source low-cost FFF machine. In their research they varied the layer thickness (0.2540 and 0.3302 mm) printing with 100% infill. Their results showed that the layer thickness of low-cost machines has higher effect on the tensile stress of the specimen. This means, in order to get higher tensile stress, the parts fabricated using the low-cost FDM machine must use lower layer thickness setting. Concerning the compression test the results were pretty close which shows that the low-cost FDM machines are reliable in fabricating small parts. For achieving these results the following parameters should be taken into consideration: small layer thickness (< 0.1 mm); orientation of 45°/−45°; and negative air gap. Rajpurohit and Dave [18] also conducted research on an open-source FFF machine. They focused on the flexural strength of PLA (Polylactic acid) parts fabricated on an open-source FFF machine and how it is influenced by the following process parameters: raster angle, raster width and layer height. They concluded that the flexural strength decrease with the increase of the raster angle and the layer height. Regarding the raster width the intermediate values provide the higher flexural strength.

Torres et al. [19] used Design of Experiments (DoE) to explore the tensile and fracture properties of the fabricated PLA part. Following process parameters were taken into account: layer thickness, density or infill percentage, extrusion temperature, speed, infill direction, and component orientation. Layer thickness could then be lowered with little concern to decreased strength, as has been previously shown. Though this would decrease strength, an increase in the number of perimeter layers could be used to reduce the negative effect, decreasing the amount of hollow space. For components which will experience negligible mechanical loading, relative density may be sacrificed to the lower setting as strength will not be an issue and an increase in perimeter layers could be used to prevent it from being too fragile so that mishandling the component would not cause damage. Taylor et al. [20] conducted a research on the mechanical properties (flexural properties, specifically modulus and yield strength) of Ultem 1010 coupons. Build orientation, raster angle and working temperature were varied for the experimental analysis and virtual simulations. The date from the experimental analysis and simulation were found to be within good agreement. For the elevated flexure testing up to 205°C (400°F), as expected, both modulus and yield strength of Ultem 1010 decreased as the testing temperature increased.

Table 1: *Classification on researches on mechanical properties of fabricated parts via FFF*

Ref	Mater | Machine | Standard	Variable parameters	Testing	Findings
[2]	ABS | Stratasys 1650 | ASTM D5937-96	6 build orientations, 4 raster orientations	Tensile testing, termal expansion,	Build orientation strongly affects the tensile strength, the elastic modulus and the thermal expansion coefficient of fabricted parts.
[11]	ABS 400 | Stratasys 1650 | ASTM D638, D790, 256-88	5 layer orientations (45/-45,0,45,90, 45/0)	Tensile, flextural and impact testing	Tensile testinge showed that the highiest UTS and yield strengths are achived in the 0° orinetation, as well as the modulus of rupture. The Izod impact test data indicated that the 0° orientation samples had the highest absorbed energy values.
[21]	ABS P400 | Stratasys 1600 | ASTM D3039	Mesostructure, air gap	Tensile testing	Mesostructure has a significant influence on the stress-strain response. Modulus values 11-37% lower and strength values 22-57% lower than the ABS monofilament were observed for the fabricated parts. The highest stiffness and strength values were found for an aligned mesostructure with a small negative air gap.
[4]	ABS | Stratasys 1650, ASTM D638, D3039	RA, RW, air gap	Tensile and compressive testing vs injection molding	At a RA of 0° and air gap of -76.2 µm, the tensile strength increases by about 30%. The RW does not affect the tensile strength.
[3]	ABS | Stratasys 1650 | ASTM D5937-96, ASTM D790-96	Build orientation, RA	Tensile and flexural testing	Mechanical properties depend on the build orientation and the RA. The samples placed in XZY show the highest values for the maximum tensile strength and Young's modul. Samples placed in ZXY show the lowest values for peak tensile strength and Young's modul.

[22]	ABS | Stratasys 3000 |	Layer thickness, RA, RW, air gap (3 levels each)	Elasticity testing	All the parameters have heavy influence on the elasticity.
[8]	ABS | Stratasys | ASTM D695	Build orientation	Compressive testing	Build direction has strong influence in the mechanical properties. Compressive strength is 11.6% higher when the build direction is axial than transversal.
[23]	ABS P400 | Stratasys 2000 | ASTM D1184-98	Build orientation, envelope temperature	Thermal and flextural testing	Envelope temperature and the cooling conditions have strong repercussions on the flextural properties as well as the accurancy of the final part.
[24]	ABS P400 | Stratasys Vantage SE | ISO R527:1966, ISO R178:1975, ISO 179:1982	Layer thickness, orientation, RA, RW, air gap	Tensile, flexural and impact testing	Optimized factors for tensile, impact and flexural strength of specimen using the bacterial foraging technique.
[6]	ABS P400 | Stratasys Vantage| ASTM D638, D790	layer thickness, build orientation, RA, RW, air gap (3 levels each)	Tensile testing, flextural testing	Tensile and flextural strength decrease with the increase of the angle with the build plate.
[14]	ABS P400 | Stratasys Vantage | ISO R527:1966, ISO R178:1975	Layer thickness, orientation, RA, RW, air gap	Tensile, flexural and impact testing.	By changing the raster angle from 60°/-30° to 90°/0°, the value of the maximum tensile stress decreases. At a positive value of the air gap, the material "flows" between adjacent layers, which leads to an increase in the maximum tensile strength. For flextural strength the parameters were found to be the same, but it differed in factor levels for impact strength.
[16]	PC | Stratasys Vantage	RA, RW, air gap (3 levels each)	Tensile testing	Highiest values for the tensile strength are achived with raster angle 45°/-45° and raster width 0.60064 mm.
[25]	ABS P400 | Stratasys Vantage | ISO R291:1977	Layer thickness, orientation, RA, RW, air gap	Compressive testing	The developed relationship between compressive stress and process parameters is able to explain the 96.13% of variability in the response.
[26]	Ultem 9085 | Stratasys Fortus 400mc | ASTM D638	RA, CW, air gap (3 levels each), layer thickness (2 levels)	Tensile testing comparison to injection molding	The best results were achieved for all directions by using a negative raster air gap. With thick filaments better mechanical data can be achieved for the X and Z build direction, while a thinner filament improves the strength properties for Y-specimen.
[27]	ABS | Stratasys Dimension SST-768	RA (4 levels)	Tensile, flexural and impact testing.	Specimens with raster angle of 45°/-45° (crisscross) had higher strength for deflection, flexural and impact tests. The tensile test result showed higher strength in cross-orientation (0°/90°).
[7]	ABS P400 | Stratasys Vantage SE | ISO 604-1973, ISO R291:1977	Layer thickness, build orientation, RA, RW, air gap (3 levels each)	Compressive testing (analytical and experimental)	Maximal compressive strength can be achived with layer thickness of 0.254 mm, orientation of 0.036°, RA 59.44°, RW 0.422 mm and air gap 0.00026 mm. Low part strength is caused by distortion and anisotropy.
[28]	ABS M30 | FDM | ASTM D638-10	Build orientation, number of contures	Tensile testing, stiffness	The results have been processed for the determination of the Ultimate Strength and of the Young’s modulus. Design of an algorithm able to model the rupture event of every single bead and, consequently, to predict the failure of the whole part.
[29]	ABS, ABS+ | Stratasys Dimension, Dimension Elite | ISO 527-1	Build orientation	Tensile testing for fatigue	ABS+ part's properties were found to be isotropic than properties of ABS parts. The UTS for the ABS specimens ranged from 50-80% of the ABS wire data and for the ABS+ specimens ranged from 75-80% percent (omitting the Z-direction).
[30]	PC | Stratasys Vantage SE | ASTM D638	Build orientation	Tensile testing, elastic modulus	The results also show a degradation in strength compared to bulk material properties (30%–53%, depending on orientation) and as manufactured properties as reported by the FDM vendor (36%–63%, depending on orientation
[31]	ABS | Stratasys Dimension BST | ISO R527:1966, ISO 180:1982	Build orientation (5 levels)	Tensile and compressive testing	The build orientation has more influence on the compressive strength than tensile strength. Compared to the injection molded parts, tensile strength is lower for 48-60 % and compressive strength has a reduction in the range of 57- 64 % for build orientation varying from 0°-90° respectively.
[32]	PLA | Bits - Bytes 3DTouch | ISO 178:2010, ISO 5271:1996, ISO 180:2001	Build orientation, infill pattern/density, layer thickness, print speed	Tensile, flexural and impact testing	Combination of impact (X oriented) and flexural (Z oriented) tests are more practical for assessing impact strength and flexural modulus when applied to parameter set B specimens, and hence the quality of a build on a FDM machine.
[13]	ABS | Fortus 400mc |ISO R527:1966, R178:1975	RA, RW, air gap, layer thickness, positioning	Tensile testing	Improvement in tensile strength is achieved with minimum layer thickness and raster width, larger raster angle, and negative air gap.
[5]	PC | Fortus 900 mc | ASTM D638	RA, RW, CW, air gap, build orientation	Tensile testing	Maximum tensile strength is achieved for the specimens placed in the XZY position, and the lowest for those placed in the ZXY position.
[12]	ABS P400 | Stratasys FDM | ASTM D638, ASTM D790	Part orientation, layer orientations	Tensile and flextural testing	Maximum flextural strength is achived with specimens placed at an angle of 0° to the x-axis. Maximum tensile strength is achived for specimens placed at an angle of 0° to the y-axis have a good maximum tensile stress. The specimens at an angle of 45° with respect to the z axis have the worst results.

[33]	ABS, PLA | Lulzbot Prusa, Prusa Mendel | ASTM D638	Layer thickner, raster orientation	Tensile testing	Investigated the association between raster pattern and a layer height of open source printers to tensile strength, modulus and strain at tensile strength.
[34]	ABS P430 | Dimension 3D Printer | ISO 178:2006, ISO 527:1997	RA (5 levels), build orientation (3 levels)	Compressive strength	Smaller raster angles (0°) provide maximum strength because of larger effective raster length.
[17]	ABS | low-cost FFF, commerical FDM	Layer thickness, build orientation, air gap	Tensile and compressive testing	FFF open-source parts reached lower values for the tensile strength. For the compressive strength the results were almost same. For optimal results lower layer thickness, orientation 45°/−45° and negative air gap are advised.
[35]	PP (polypropylene), GRPP (glass reinforced PP) | Prusa i3 | DIN 53504-S3a	infill degree, build orientation, layer thickness	Tensile and compressive testing	The adhesion between adjacent filaments is evident but, and the samples are stiffer in the filament direction. The layer thickness has little influence on the mechanical performance of the samples. The infill degree has a dramatic and linear effect on the mechanical properties. The use of fibers as reinforcement is also effective in 3D printing. The loss in the mechanical performance of the printed samples is 20–30%, depending on the printing parameters values used, when compared to that of samples produced by compression molding.
[36]	ABS | Stratasys Vantage | ASTM D638, ASTM D7791	raster orientation (4 levels), defined machine default values for parameters	Tensile and fatigue testing	UTS and yield strength are highest for 0° raster orientation.
[37]	PLA | Prusa | ASTM D638	layer thickness, print orientation (2 levels each), infill percentage (3 levels)	Tensile testing, elastic modulus	The decrease in strength was observed as infill orientation comes closer to 90° and increases when perimeters increase.
[38]	PA12 (polyamide) | Fortus 400mc | DIN EN ISO 527, DIN EN ISO 178, DIN EN ISO 604, DIN EN ISO 1133	Layer thickness, build orientation (3 levels each)	Tensile, flexural, compressive testing, thermal testing	The highest tensile strength was recorded in X-direction. No anisotropy was visible for the flexural strength but a slight tendency for the flexural modulus. The highest compressive modulus is noticeable in Z-direction with a layer thickness of 254 µm. For the compressive strength, there are only slight differences recognizable. As thermal properties of the Polyamide 12, the flow ability is determined (MVR) and the melting behavior by means of DSC analyze.
[15]	ABS | Cubex 3D printer | ASTM D-1708, ASTM D-256, ASTM D785	Layer thickness	Tensile, impact and hardnes testing	The layer thickness plays a significant role in the mechanical propertied of ABS fabricated parts. As the layer thickness increases, tensile strength reduced by 46%, impact strength reduced by 54.5% and hardness reduced by 40%; exception is with layer thickness 0.5 mm.
[39]	ABS | Lulzbot TAZ 4 | ASTM D638-10	Build orientation, raster patterns	Tensile testing	The tensile test results exhibited an equivalency between the vertically printed specimens with horizontal printed specimens. The fracture morphology was also planar in nature and exhibited less plastic deformation than the longitudinal and crosshatched specimens.
[19]	PLA | Replicator 2 | ASTM D638; D648, E143	layer thickness, build orientation, infill percentage and direction, extrusion temperature, speed (2 levels each)	Tensile and flexural testing	Layer thicknes and infill percentage have highies influence on the tensile and flexural strength.
[40]	Z-ABS, Z-Ultrat, Z-glass-PETG | Zortrax | EN ISO 527-4 type 5	5 samples for each material	Tensile testing	Results show some distinctions between tensile modulus of the fabricated parts and its base materials, i.e. Z-ABS prints Young modulus have mean value of 1.12 GPa and the encyclopedic value is between 1.7 up to 2.1 GPa.
[9]	Z-ABS | Zortrax M200 | ASTM D638	layer thickness , build plate, and build orientation (3 levels each)	Tensile testing, compession testing	Specimens with layer thickness of 0.09 mm and YZ-H show the highest Young's modulus of 1524 MPa. YZ-H and YZ-D with layer thickness of 0.09 mm show the highest yield strength of 39 MPa. Compression tests show that XY-H and XY-D have the highest stiffness and yield strength.
[41]	Ninjaflex (5 colors), SemiFlex (4 colors), HIPS (5 colors), T-Glass (5 colors), PC (1 color), Nylon (2 Types), ABS (1 color) | Lulzbot TAZ 3.1 and 4 | ASTM D638	Different extrusion temperature for different materials, mass	Tensile testing	The study demonstrates that the tensile strength of fabricated specimens depends largely on the mass of the specimen, for all materials. The strongest material among those tested was polycarbonate with a maximum tensile strength of 49 MPa. The most flexible material was Ninjaflex, which did not break after an extension of about 800%. Nylon materials were stronger than Ninjaflex and SemiFlex, and much more flexible than ABS, HIPS, T-Glase, and polycarbonate, which provides a good balance between strength and flexibility.
[20]	Ultem1010 | FDM	build orientation, RA, air gaps	Flextural testing	The XYZ 0°/90° build combination was chosen for elevated temperature flexure testing. For the elevated flexure testing up to 205°C (400°F), both modulus and yield strength decreased as the testing temperature increased. Similarly to the elevated temperature tests, the XYZ 0°/90° build combination was chosen for sparse-build flexure coupons. The experimental and simulation data were found to be within good agreement.

[42]	PLA | WitBox desktop 3D printer | ASTM D638, ASTM D790	Build orienatation, feed rate (3 levels each), layer thickness (4 levels)	Tensile and flextural testing	On-edge orientation may be selected for the optimal mechanical performance in terms of strength, stiffness and ductility. If ductile behaviour is desired with the optimal printing time, strength and stiffness, high layer thickness and low feed rate values are recommended for upright and on-edge orientations. Low layer thickness and high feed rate values are recommended for on-edge and flat orientations. If minimum printing time is desired, high layer thickness and high feed rate are recommended.
[18]	PLA | FFF open-source	Layer thickness, RA, RW	Flextural testing	A higher flexural strength was observed at 0° RA and decrease with highier angle and higher layer thickness. At the intermediate value of the RW, a higher flexural strength is achived.
[10]	PPSF | FDM |	Build orientation, RA, RW, air gap	Tenisile and flexural testing	The best physical and mechanical PPSF characteristics, are achieved by printing in a longitudinal filament orientation, with minimum width and negative air gaps between them.
[43]	PLA, PC, PETG | Prusa Mk3S | ISO 527-1:2019, ISO 178:2019	100% infill, change in material	Tenisile and flexural testing	PLA specimens have the highies tensile strength, largest mean Young's modulus and flextural stress. PETG showed the largest elongation before breaking in both test cases. PC specimens have the highes UTS.

4. Discussion

As can be noted from Table 1, most of the researches are conducted for ABS parts, as this material is most widespread. But in the last few years studies on different materials emerge, such us: PLA and Ultem. As can be seen from the Table 1 there is not unified standard used for testing of the fabricated specimens, since the standardization for AM is still in its infancy. This is one element that really makes it difficult for the researchers not being able to compare results, working under different standards. ASTM and ISO has joined forces into creating standards faster, but AM technologies are consisted on many different processes that use different materials and consequently work under different working conditions.

Most of the presented studies focus on the tensile and flexural properties of the specimens, but not all of them concentrate on the same process parameters. From Table 1 can be concluded that there is high connection between the mechanical properties and the part or layer orientation as well as the layer thickness. There are also important parameters such us: working temperature, speed, which are not subject of concern in many studies.

5. Conclusion

In this study more than 40 paper dealing with the mechanical properties of the fabricated parts with FDM and FFF were reviewed. From the stated facts and analyzed papers it can be concluded that FFF process has come a long way since its beginnings, the materials and the machines are more advanced capable of fabricating parts with decent mechanical properties. Although it should be noted that many elements such as working environment, process parameters, used material, machine have influence on the mechanical properties of the final part. This is why the application of the part should be taken into consideration in the design phase and according to that the appropriate process and process parameters will be chosen.

It is important to be noted that these processes are not meant to substitute the conventional technologies such us injection molding and there for comparison is not necessary. These processes are meant to create new opportunities and enable application in areas that were not expected.

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