Analysis of material properties in respect of material interior styles used in Fused Deposition Modeling

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Abstract: Fused Deposition Modeling (FDM) is put in category of Rapid Prototyping methods and can be used to help introduce manufacturing projects or as a stand-alone manufacturing technology (Direct Digital Manufacturing). In both cases it is necessary to verify printout's behavior under workload. This elaboration presents complete analysis of material properties in respect of material interior styles.

FDM is an additive technology that builds horizontal layers of liquefied plastic material, one on each other, which leads to creation of a complete part. Work head is an extruder that is moved by a gantry type manipulator. It uses two types of plastic material, model and support (creates scaffolding that allows manufacturing of complex three-dimensional parts). Process management software (Insight) provided by Stratasys Inc. enables usage of various types of material interior styles. That has major influence on printing time and on material properties of a part. Diameter of distributed filament is specified by diameter of a tip installed on work head and that allows to create material layers of differentiated thickness, i.e. 0,127, 0,178, 0,254, 0,33 mm. Usage of a wider tip shortens production time but also limits ability to build detailed and complex parts.

There are several types of material used in FDM nowadays. This article presents the complete analysis of material interior styles, created in respect of three types of materials – copolymer of Acrylonitrile, Butadiene and Styrene, polycarbonate and polyetherimide under the name of Ultem 9085.

Keywords: fused deposition modeling, rapid prototyping, interior style, 3D printing, flexural strength, impact resistance, tensile strength

1. Introduction

Fused Deposition Modeling (FDM) is belong to category of Rapid Prototyping methods and can be used to help introduce manufacturing projects or as a stand-alone manufacturing technology (Direct Digital Manufacturing). In both cases it is necessary to verify printout's behavior under workload. This elaboration presents the complete analysis of material properties in respect of material interior styles.

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There are several types of material used in FDM nowadays. This elaboration presents the complete analysis of material interior styles, created in respect of three types of materials provided by Stratasys Inc. – copolymer of Acrylonitrile, Butadiene and Styrene, polycarbonate and polyetherimide under the name of Ultem 9085 consecutively later called ABS-M30, PC and Ultem 9085. Material samples have been created in six ways, as Fig. 1 shows. T12 tips (Ø 0,178 mm) have been used for both model and support layers.

Introductory examination of samples allowed determination of their density. Any examination or test has been carried out in accordance with ISO restrictions (*Plastics. Determination of charpy impact test* – PN-EN ISO 179-2:2001, *Plastics. Determination of flexural properties* – PN-EN ISO 178:2011, *Plastics. Determination of tensile properties* – PN-EN ISO 527-2:1998). Five samples have been tested for each and every interior style.

Fig. 1. Types of interior styles. From left: Lengthwise filament distribution (Solid, Sparse, Sparse Double-Dense), Crosswise filament distribution (Solid, Sparse, Sparse Double-Dense)

Rys. 1. Rodzaje wypełnienia warstwy. Od lewej: podłużne rozprowadzanie tworzywa (Solid, Sparse, Sparse Double-Dense), poprzeczne rozprowadzanie tworzywa (Solid, Sparse)

2. Results

Printing process control along with Pro/ENGINEER CAD software allowed determination of density of Solid interior style. Basing on that, densities of Sparse and Sparse Double-Dense interior styles have been calculated. It has been verified that a major part weight reduction can be achieved, i.e. for polycarbonate it reaches over 60 %. Following table shows weight reduction achieved for every interior style.

Static tension test showed breaking points which have been calculated as arithmetic means of results given by five samples for every interior style. Deviations from those averages have been also calculated and that shows homogeneousness and fusion of filaments.

In case of Solid and Sparse interior style usage, polycarbonate and polietherimide under the name of Ultem 9085 samples break gradually without necking. Consecutive filaments, not being able to withstand increasing tension, break unexpectedly which results in high deviations in test results. Using Sparse Double Dense interior style changes this situation radically because it binds filaments altogether by creating a truss on each layer of material. Samples behave more predictably so after reaching their breaking points, samples rupture in their whole cross-section instantly.

Weight reduction causes downturn in tensile strength for all materials provided by Stratasys Inc. Application of Sparse Double-Dense interior style causes twice as low loss in tensile strength as Sparse interior style but it allows to reduce part

Tab. 1. Densities of material interior styles and weight reduction in comparison to Solid interior style

Tab. 1. Zestawienie gęstości w zależności od wypełnienia oraz redukcji masy w porównaniu do wypełnienia Solid

	Density [g/cm^3]		
Interior style	ABS-M30	PC	Ultem 9085
Solid	2,05	2,26	2,44
Sparse	1,24	0,87	1,26
Sparse Double-Dense	1,34	1,06	1,45
Weight reduction in comparison to Solid [%]			
Sparse	39,38	61,25	48,28
Sparse Double-Dense	34,75	53,13	40,40

Fig. 2. Collation of samples after tensile strength test. From left: ABS-M30, PC, Ultem 9085. From top: Lengthwise filament distribution (Solid, Sparse, Sparse Double-Dense), Crosswise filament distribution (Solid, Sparse, Sparse Double-Dense)

Rys. 2. Zestawienie próbek po teście statycznego rozciągania. Od lewej: ABS-M30, PC, Ultem 9085. Od góry: podłużne rozprowadzenie tworzywa (Solid, Sparse, Sparse Double-Dense), poprzeczne rozprowadzenie tworzywa (Solid, Sparse, Sparse Double-Dense)

Tab. 2. Collation of breaking points [kN] in respect of all interior styles

Tab. 2. Zestawienie sił zrywających [kN] dla poszczególnych wypełnień

		Interior style					
	Material	Lenghtwise Solid	Lenghtwise Sparse	Lenghtwise Sparse Double-Dense	Crosswise Solid	Crosswise Sparse	Crosswise Sparse Double-Dense
Breaking point [kN]	ABS-M30	1,62	1,20	1,21	1,06	0,62	0,81
	PC	2,44	1,22	1,60	1,12	0,57	0,98
	Ultem 9085	3,33	2,05	2,28	1,25	0,90	1,13
Highest deviation from breaking point [%]	ABS-M30	2,72	1,67	2,65	5,66	7,05	4,70
	PC	6,56	18,42	1,00	11,76	16,96	7,14
	Ultem 9085	4,63	15,98	13,36	13,74	14,44	2,48

Tab. 3. Percentile downturn of tensile strength in comparison to Solid interior style

Tab. 3. Procentowy spadek wartości siły zrywającej względem wypełnienia Solid

	Lenghtwise Sparse	Lenghtwise Sparse Double-Dense	Crosswise Sparse	Crosswise Sparse Double-Dense
ABS-M30	25,74	25,25	41,13	23,77
PC	50,16	34,59	49,55	12,66
Ultem 9085	38,30	31,57	28,12	9,90

weight by up to 53,13 %. In case of Sparse interior style weight reduction can top 61,25 % but material behaves unexpectedly and delamination occurs.

Regarding to chosen interior style, different results in unnotched Charpy impact test have been achieved. Copolymer of Acrylonitrile, Butadiene and Styrene (ABS-M30) can be characterized as the weakest material in mentioned test. Huge difference between impact resistances occurs in respect of lengthwise and crosswise interior types. It is so because impact is suppressed by elongation of filaments in lengthwise interior style. On the other hand, in crosswise interior styles, stress is being handled only by seams in material. Those seams are formed by consecutive layer fission (Fig. 3b).

There is not much discrepancy in results in respect of interior styles in same direction of filaments. Lengthwise Solid, Sparse and Sparse Double-Dense have similar ability to withstand high velocity impact and about five times higher than each and every crosswise interior style. Undermentioned table shows percentile comparison of impact resistances achieved by Sparse and Sparse Double-Dense interior styles to consecutive Solid (with lengthwise and crosswise filament distribution).

Sparse and Sparse Double-Dense interior styles of polycarbonate samples achieves better results in impact test.

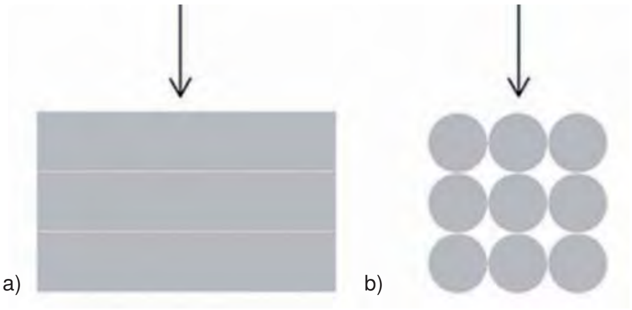

Fig. 3. Cross-section of a part, view normal to build platform, same direction. From left: a) lengthwise interior style, b) crosswise interior style. Arrows show impact vector

Rys. 3. Przekrój przez część, widok normalny do płaszczyzny bazowej w tym samym kierunku. Od lewej: a) podłużne rozprowadzenie tworzywa, b) poprzeczne rozprowadzenie tworzywa. Strzałki ukazują wektor uderzenia

Tab. 4. Impact resistance [kJ/m^2] for all interior styles

Tab. 4. Udarności [kJ/m^2] dla poszczególnych wypełnień

	Interior style					
Material	Lenghtwise Solid	Lenghtwise Sparse	Lenghtwise Sparse Double-Dense	Crosswise Solid	Crosswise Sparse	Crosswise Sparse Double-Dense
ABS-M30	113,75	102	107,25	9,5	7,75	8,25
PC	130,25	139,75	140,5	13,5	15,5	15,75
Ultem 9085	155	151,5	154,25	33,75	32,5	34

Tab. 5. Percentile change in impact resistance in comparison to Solid interior style

Tab. 5. Procentowa zmiana udarności względem wypełnienia Solid

	Lenghtwise Sparse	Lenghtwise Sparse Double-Dense	Crosswise Sparse	Crosswise Sparse Double-Dense
ABS-M30	−11,52	−6,06	−22,58	−15,15
PC	6,80	7,30	12,90	14,29
Ultem 9085	−2,31	−0,49	−3,85	0,74

Tab. 6. Flexural modulus [GPa] in respect of all interior styles

Tab. 6. Wytrzymałość na zginanie [GPa] dla poszczególnych wypełnień

	Lengthwise Solid	Lengthwise Sparse	Lengthwise Sparse Double-Dense	Crosswise Solid	Crosswise Sparse	Crosswise Sparse Double-Dense
ABS-M30	0,2395	0,2053	0,6098	0,4529	0,7184	0,8065
PC	0,2358	0,2097	0,7225	0,4464	0,601	0,8065
Ultem 9085	0,2395	0,2053	0,6098	0,4529	0,7184	0,8065

Tab. 7. Percentile change in flexural modulus in comparison to Solid interior style

Tab. 7. Procentowa zmiana wytrzymałości na zginanie względem wypełnienia Solid

	Lengthwise Sparse	Lengthwise Sparse Double-Dense	Crosswise Sparse	Crosswise Sparse Double-Dense
ABS-M30	-16,66	60,72	36,96	43,84
PC	-12,45	67,36	25,72	44,65
Ultem 9085	-16,66	60,72	36,96	43,84

This happens because PC is a very hard and durable material but is not very pliable. In both cases, of lengthwise and crosswise filament distribution, material is allocated in a way that air gaps between each fiber are created. That allows it to bend a little, thus absorb more energy. Therefore using less material (up to 60 % weight reduction) can fabricate a part that has up to 15 % higher impact resistance. On the other hand, ABS-M30 copolymer and polyetherimide are more flexible than polycarbonate, therefore weight (and by that amount of fibers) reduction can result in falloff in impact resistance.

Young' modulus for every interior style has also been calculated, basing on results of flexural properties test (PN-EN ISO 178:2011). Table 6. shows results of undertaken investigations.

Basing on given results, comparison of interior styles for corresponding filament distribution types has been calculated.

Best results have been achieved by Sparse Double-Dense interior style in both cases (lengthwise and crosswise filament distribution). This happens because it creates a truss on each layer of material. That binds all filaments altogether resulting in fabrication of a very durable, strong and firm part. On the other hand, air gaps allow samples to bend a little, so it results in offering good impact resistance. As a result, weight reduction of 34,75 %, 53,13 % and 40,4 % adequately for ABS-M30, PC, Ultem 9085 can lead to creation of a part that can sustain a lot higher workload.

Noticeable difference in flexural strength between Sparse lengthwise and crosswise filament distribution appears because filament segments in crosswise fiber allocation type are a lot shorter than in lengthwise type (Fig. 1). Therefore, sample cannot bend as much as with lengthwise filament distribution, resulting in better flexural strength properties.

3. Conclusion

High discrepancy in achieved results in respect of different interior styles and filament distribution types proves that choosing proper fiber allocation method is a fundamental step in the part planning. Projects can be verified thoroughly, before any manufacturing's been implemented. That allows to save a lot of time and money on prototype creation and helps to produce parts that have proper material properties (tensile, flexural strength, impact resistance) that have been especially designed and tested for a given workload and part life span. Most important asset of interior style strategy is weight reduction. Extraordinary results (reduction up to 61,25 % in case of polycarbonate Sparse interior style) can be achieved. On the other hand, falloff in material properties has been noticed. Evaluation of pros and cons for each and every interior style and filament distribution type shows that best choice for most cases is Sparse Double-Dense interior style. As expected, lengthwise fiber allocation method gives better results in tensile and flexural strength tests as well as in unnotched Charpy impact test. Moreover, significant weight reduction, 34,75 %, 53,13 %, 40,4 % and density of 1,34 g/cm^3, 1,06 g/cm^3, 1,45 g/cm^3 adequately for ABS-M30, PC and Ultem 9085, can be achieved allowing to produce part that are tough, durable and very light. This enables production of parts i.e. for aerospace, robotics and automobile industries that require good, predictable material properties followed by low mass.

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Analiza technologii Fused Deposition Modeling oraz wpływu wypełnienia detali tworzywem na ich właściwości wytrzymałościowe

Streszczenie: Technologia osadzania topionego materiału (FDM) zaliczana jest to metod szybkiego prototypowania i może być wykorzystywana jako pomoc przy wdrażaniu projektu produkcyjnego lub jako technologia wytwarzania. W obu przypadkach konieczne jest określenie sposobu zachowania się wydruku pod obciążeniem. Niniejsze opracowanie przedstawia analizę wpływu wypełnienia detali tworzywem na ich właściwości wytrzymałościowe. FDM jest technologią addytywną, polegającą na układaniu, jedna na drugiej, poziomych warstw upłynnionego tworzywa na platformie roboczej, co prowadzi do nabudowania kompletnego elementu. Głowica robocza jest wytłaczarką poruszaną przez manipulator w układzie bramowym. Wykorzystuje ona dwa rodzaje materiału, podporowy (tworzy rusztowanie umożliwiające wytworzenie skomplikowanych przestrzennie modeli) i budulcowy. W obu przypadkach oprogramowanie do obsługi procesu drukowania – Insight firmy Stratasys – umożliwia zastosowanie różnego rodzaju wypełnień, wpływających na czas drukowania, jak również na właściwości materiałowe detalu. Grubość nitki nakładanego tworzywa zależy wyłącznie od zastosowanej końcówki roboczej, co umożliwia rozprowadzanie warstw o grubościach 0,127, 0,178, 0,254 i 0,33 mm odpowiednio zmniejszając łączny czas procesu, co łączymy jednak z pogorszeniem zdolności odwzorowania niewielkich szczegółów w modelu. W technologii FDM stosowanych jest obecnie kilka materiałów. Niniejsze opracowanie przedstawia analizę wypełnień wykonaną w odniesieniu do trzech materiałów – kopolimeru akrylonitrylo-butadieno-styrenu o nazwie handlowej ABS-M30, poliwęglanu i polietoroimidu o nazwie handlowej Ultem 9085.

Słowa kluczowe: osadzanie topionego tworzywa, szybkie prototypowanie, wypełnienie, drukowanie 3D, wytrzymałość na zginanie, udarność, wytrzymałość na rozciąganie

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