1st Winter School, 24-28 Jan. 2021

Trends on Additive Manufacturing for Engineering Applications

Practical session 2 (Faculty of Mech. Eng. Lab., Timisoara & Online)

Testing of AM specimens (static, dynamic, fracture toughness)

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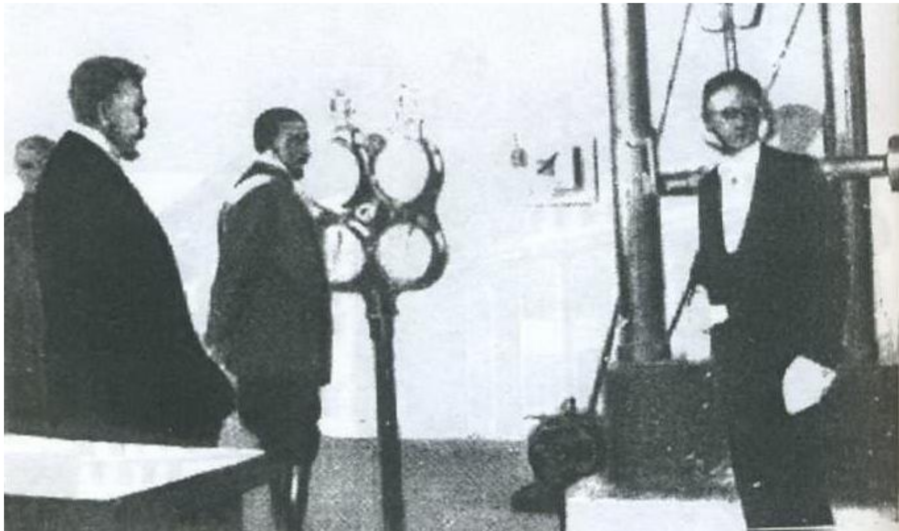
Department of Mechanics and Strength of Materials - History

- The Strength of Materials Laboratory was opened in 1923 in the presence of King FERDINAND and Prime Minister I. C. BRATIANU.
- First tests with students were held in 1923, and the first student "*Laboratory notebook*" was published in 1924.
- In 1931 the laboratory was visited by King CAROL the Second and Prime Minister N. IORGA.



Department of Mechanics and Strength of Materials

- ❑ RESEARCH CENTER IN STRENGTH OF MATERIALS AND SAFETY OF MECHANICAL STRUCTURES, CABLES AND CONDUCTORS
- ❑ RESEARCH CENTRE FOR VIBROIMPACTS AND MECHANICAL VIBRATIONS
- ❑ MEDICAL ENGINEERING RESEARCH CENTRE

Department of Mechanics and Strength of Materials

RESEARCH CENTER IN STRENGTH OF MATERIALS AND SAFETY OF MECHANICAL STRUCTURES, CABLES AND CONDUCTORS.

Research fields:

- Strength of Materials,
- Fatigue and Fracture Mechanics,
- Materials testing (metals, plastics, ceramics, cellular) under different loading conditions (static, dynamic, creep),
- Integrity and Durability of structures,
- Experimental Stress Analysis (TSA, DIC and photoelasticity),
- Numerical Stress and Strain Analysis.

Department of Mechanics and Strength of Materials

RESEARCH CENTER IN STRENGTH OF MATERIALS AND SAFETY OF MECHANICAL STRUCTURES, CABLES AND CONDUCTORS. Research infrastructure:

- static testing machines,
- fatigue testing machines,
- FLIR 40 Thermograph,
- Digital Image Correlation System Dantec,
- Instrumented Impact Charpy
- NDT ultrasonic,
- Load cells, data acquisition systems,
- Additive manufacturing equipment
- more than 50 computers,
- SolidWorks, Abaqus, Digimat, Ansys, Cosmos M, Beasy

Department of Mechanics and Strength of Materials

❑ RESEARCH CENTRE FOR VIBROIMPACTS AND MECHANICAL VIBRATIONS. Research fields:

- Mechanics,
- Vibrations (linear and non-linear),
- Acoustics,
- Nonlinear Dynamics of mechanical systems.

Department of Mechanics and Strength of Materials

MEDICAL ENGINEERING RESEARCH CENTRE. Research fields:

- Biomechanical modelling of human locomotors apparatus,
- Motion and posture analysis of the human body,
- Reverse engineering, design and numerical analysis of stress distribution in bone structures, implants, bone/implant assemblies,
- Manufacturing of prosthetic devices and components,
- Development of new testing methods for implants and prosthetic devices.

Department of Mechanics and Strength of Materials

MEDICAL ENGINEERING RESEARCH CENTRE. Research infrastructure:

- Modelling and design Laboratory
- Medical Imaging Laboratory
- Motion Analysis Laboratory
- Medical investigations Laboratory – explores many practices that arise in the field of usual medical investigations.
- Manufacturing Laboratory – CNC Machining and EDM Fabricatio
- Manufacturing Laboratory – Rapid Prototyping Fabrication
- LOPIFO Manufacturing Laboratory for implant devices, orthoses and prosthetic devices
- CIDUCOS Testing Laboratory (multiaxial Intron 25 kN testing machine)

- **Generally, there are no specific tests for AM materials/structures**
- **Usual standards are used**

Destructive testing to quantify properties of AM (Plastic components), [Forster, 2015]

Test type	Test type	Properties to be obtained and conditions	Standards
Tensile	Determination of tensile properties of plastics	Young modulus, Yield stress, Tensile strength	ASTM D638, ISO 527-2
	Determination of tensile properties of fiber reinforced composites	Young modulus, Yield stress, Tensile strength	ASTM D3039, ISO 527-4
Compression	Compression test	Compressive properties	ASTM D695, ISO 604
Shear	Plate twist method	In-plane shear modulus	ISO 15310
Bending	Flexural tests	Flexural properties	ASTM D790, ISO 178
	Four point bend test	Flexural properties	ASTM D6272
Fracture mechanics	Determination of fracture toughness	K_{IC}, G_{IC} (Linear Elastic Fracture Mechanics)	ISO 13586, ASTM 5045
	Determination of J-R curve	J-Integral versus crack growth	ASTM D6068
Fatigue tests	Determination of flexural fatigue	Fatigue strength, S-N curve	ASTM D7774, ISO 13003
	Uniaxial fatigue	Fatigue strength, S-N curve	ASTM D7791
Impact tests	Charpy impact properties (non instrumented and instrumented)	Fracture energy	ISO 179; ASTM D6110
	Izod Impact properies	Fracture energy	ASTM D256

There are no particular standards for AM materials!

BRITISH STANDARD

Plastics — Determinat
tensile prop

Part 1: General prir

INTERNATIONAL STANDARD

ISO 527-2

Second edition
2012-02-15

Plastics — Determination of tensile properties —

Part 2:
Test conditions for moulding and extrusion plastics

Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

➢ Dog bone specimens

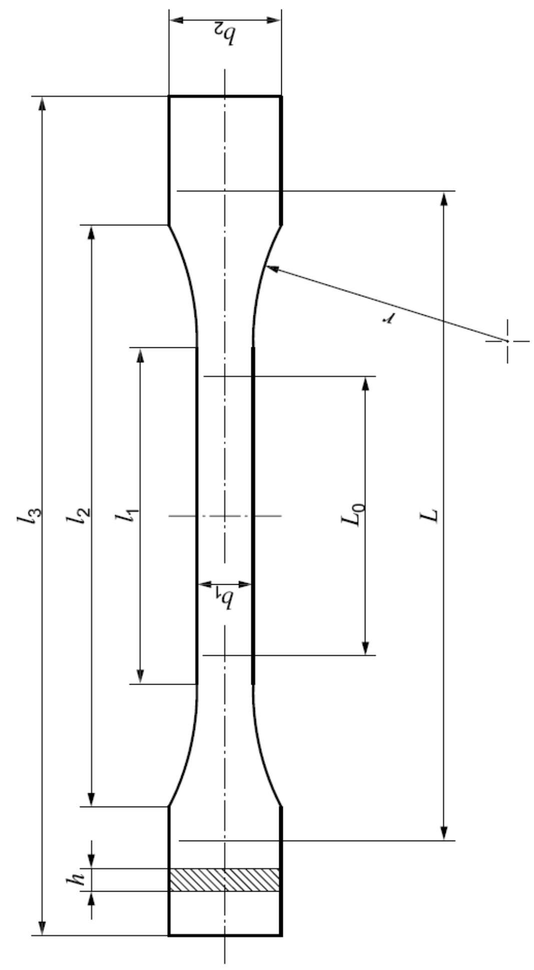
	Specimen type	1A	1B
l_3	Overall length[a]	170	≥150
l_1	Length of narrow parallel-sided portion	80 ± 2	60,0 ± 0,5
r	Radius	24 ± 1	60 ± 0,5
l_2	Distance between broad parallel-sided portions [b]	109,3 ± 3,2	108 ± 1,6
b_2	Width at ends	20,0 ± 0,2	
b_1	Width at narrow portion	10,0 ± 0,2	
h	Preferred thickness	4,0 ± 0,2	
L_0	Gauge length (preferred)	75,0 ± 0,5	50,0 ± 0,5
	Gauge length (acceptable if required for quality control or when specified)	50,0 ± 0,5	
L	Initial distance between grips	115 ± 1	115 ± 1

[a] The recommended overall length of 170 mm of the type 1A is consistent with ISO 294-1 and ISO 10724-1. For some materials, the length of the tabs may need to be extended (e.g. l_3 = 200 mm) to prevent breakage or slippage in the jaws of the testing machine.

[b] $l_2 = l_1 + [4r(b_2 - b_1) - (b_2 - b_1)^2]^{1/2}$, resulting from l_1, r, b_1 and b_2, but within the indicated tolerances.

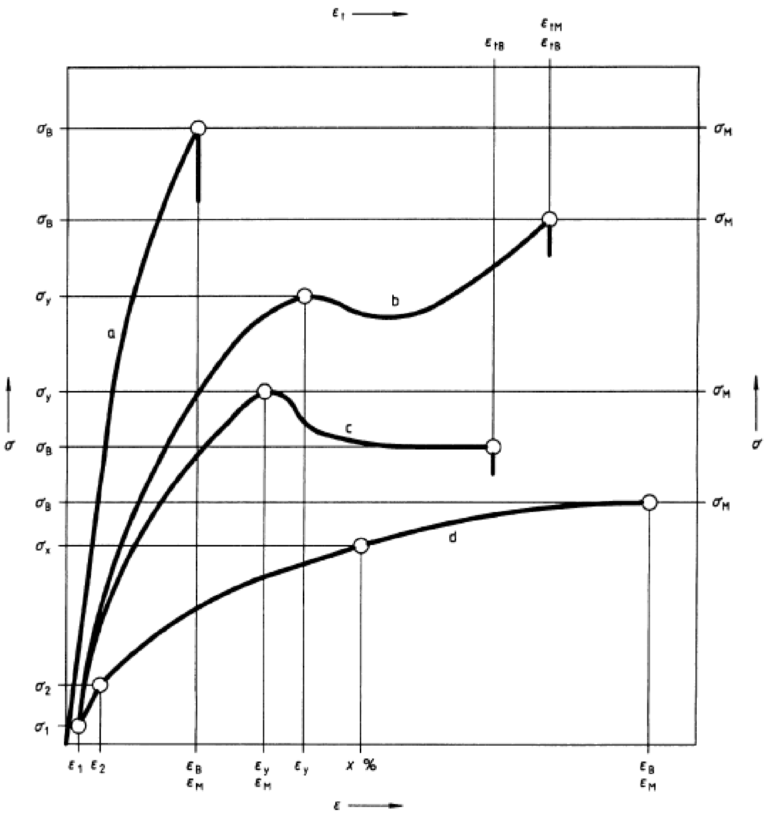
	Specimen type	1BA	1BB
l_3	Overall length	≥75	≥30
l_1	Length of narrow parallel-sided portion	30,0 ± 0,5	12,0 ± 0,5
r	Radius	≥30	≥12
l_2	Distance between broad parallel-sided portions	58 ± 2	23 ± 2
b_2	Width at ends	10,0 ± 0,5	4 ± 02
b_1	Width at narrow portion	5,0 ± 0,5	2,0 ± 0,2
h	Thickness	≥2	≥2
L_0	Gauge length	25,0 ± 0,5	10,0 ± 0,2
L	Initial distance between grips	$l_2\,{}^{+2}_{\ 0}$	$l_2\,{}^{+1}_{\ 0}$

NOTE The specimen types 1BA and 1BB are proportionally scaled to type 1B with a reduction factor of 1:2 and 1:5, respectively, with the exception of thickness.



Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

- **Typical stress – strain curves**



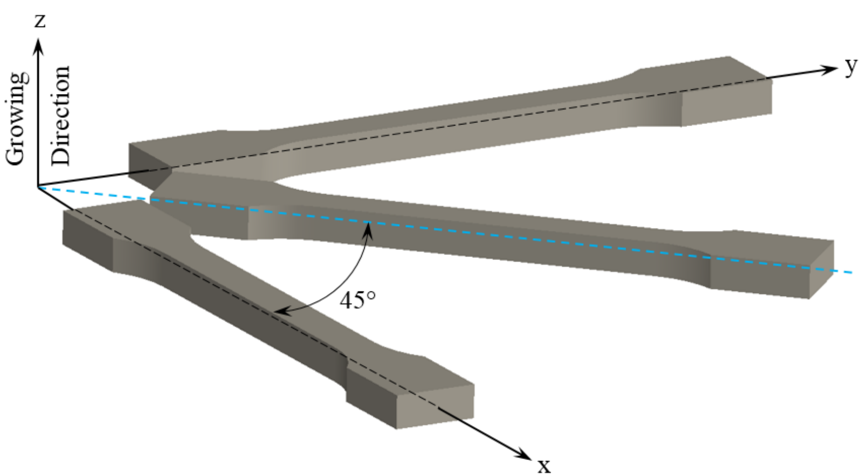
Curve a	Brittle materials
Curves b and c	Tough materials with yield point
Curve d	Tough materials without yield point

The points for the calculation of Young's modulus E_t according to 10.3 are indicated by (σ_1, ε_1) and (σ_2, ε_2), shown only for curve d ($\varepsilon_1 = 0{,}000\ 5$; $\varepsilon_2 = 0{,}002\ 5$).

Figure 1 — Typical stress/strain curves

Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

➢ **Specimens preparation**



Printer	Temp. Build plate [^{0} C]	Temp. Print [^{0} C]	Max. Speed [mm/s]	Average Speed [mm/s]	Layer thickness [mm]	Infill	Infill density [%]
Prusa MK3	60	220	80	45	0.15	Rectilinear +/-45 grade	100

Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

➢ **Results on tensile testing**

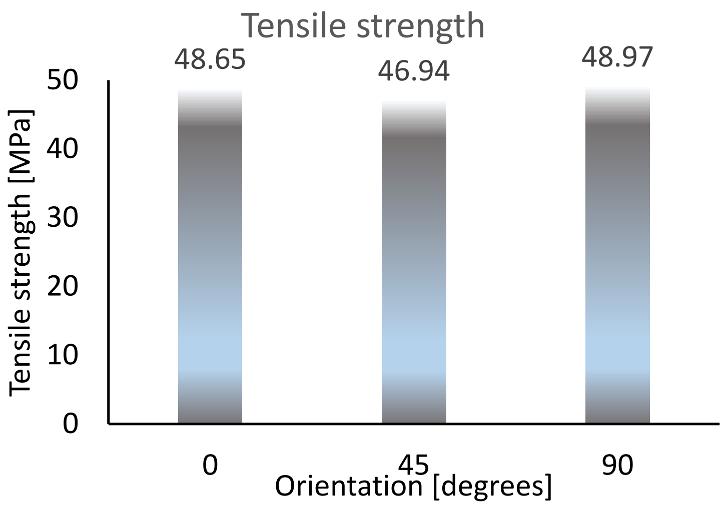
PLA	Grey	27/01/2021					
Tensile test							
Loading speed	5 mm/min						
					Stress at 2 strains		
Specimen ID	**Thickness h**	**Width b**	**Max. load**	**Tensile strength**	ε_1=0.0005	ε_2=0.0025	**Young modulus**
	h [mm]	**b [mm]**	**Pmax [N]**	**σ_r [MPa]**	**σ_1 [MPa]**	**σ_2 [MPa]**	**Young modulus E [MPa]**
H0	**3.95**	**9.94**	1910	48.65	1.82	8.18	3180.00
H45	**3.86**	**9.99**	1810	46.94	2.28	9.60	3660.84
H90	**3.92**	**9.95**	1910	48.97	2.24	9.25	3505.00

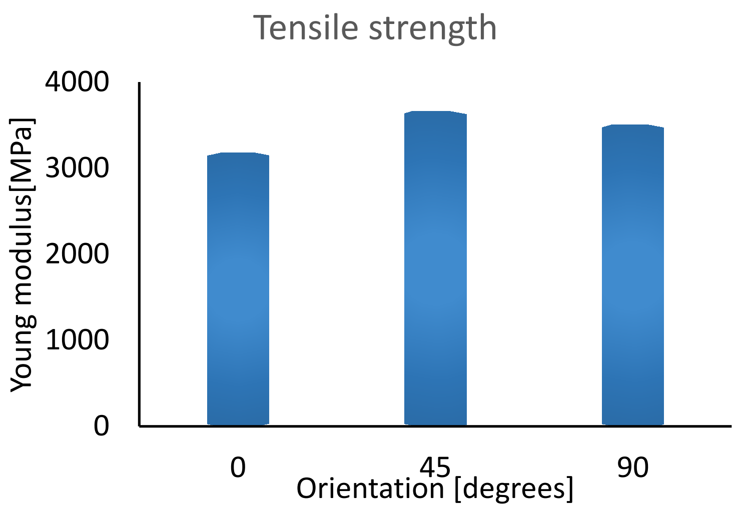
$$\sigma_r = \frac{P_{max}}{h \cdot b}$$

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

- **Results on tensile testing**

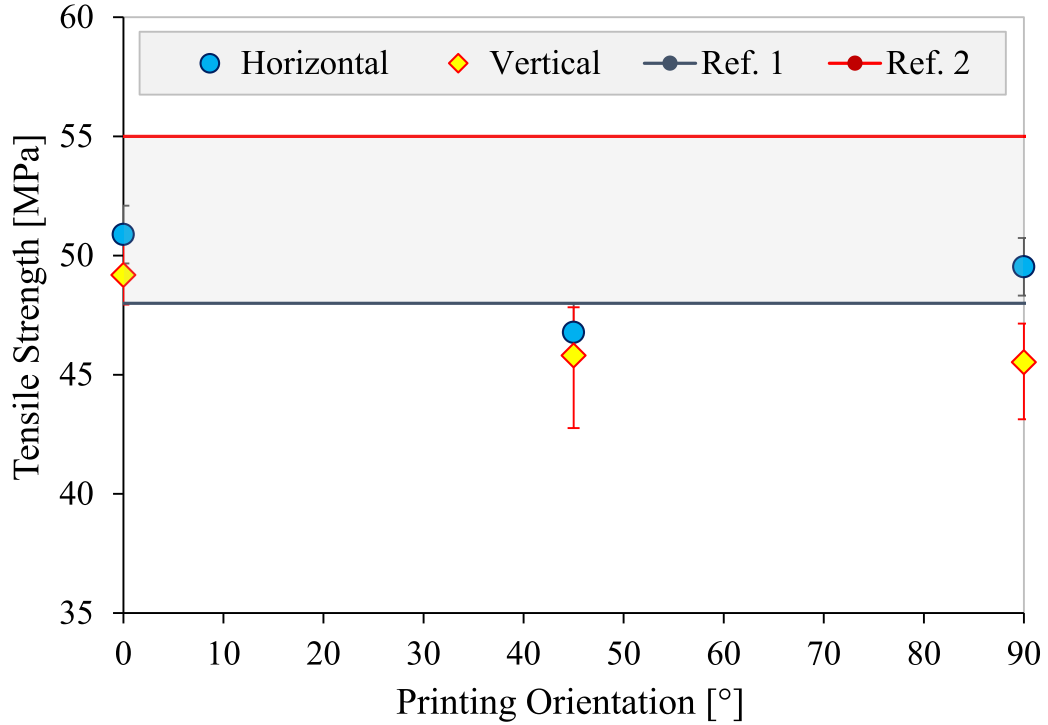




- **Similar tensile strength values for 0^0 and 90^0 orintations, lower value for 45^0**
- **The higher Young modulus for 45^0**

Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

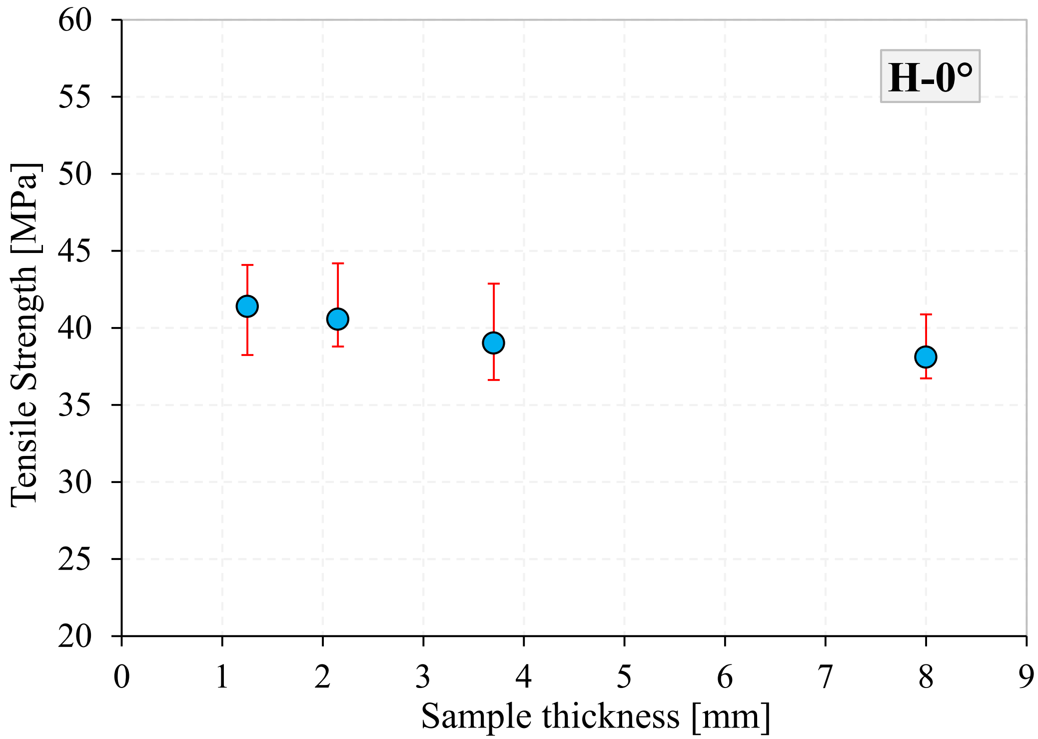
- **Some results for PLA – influence of orientation and direction, comparison with injected molded**



1. http://www.matweb.com/search/datasheet.aspx?matguid=022f6212e6e0415c9f740b3db3d1ae7e&ckck=1
2. http://www.corbion.com/media/379249/corbion-purac-ts-pla-portfolio1505.pdf

Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

➢ **Influence of specimen thickness**

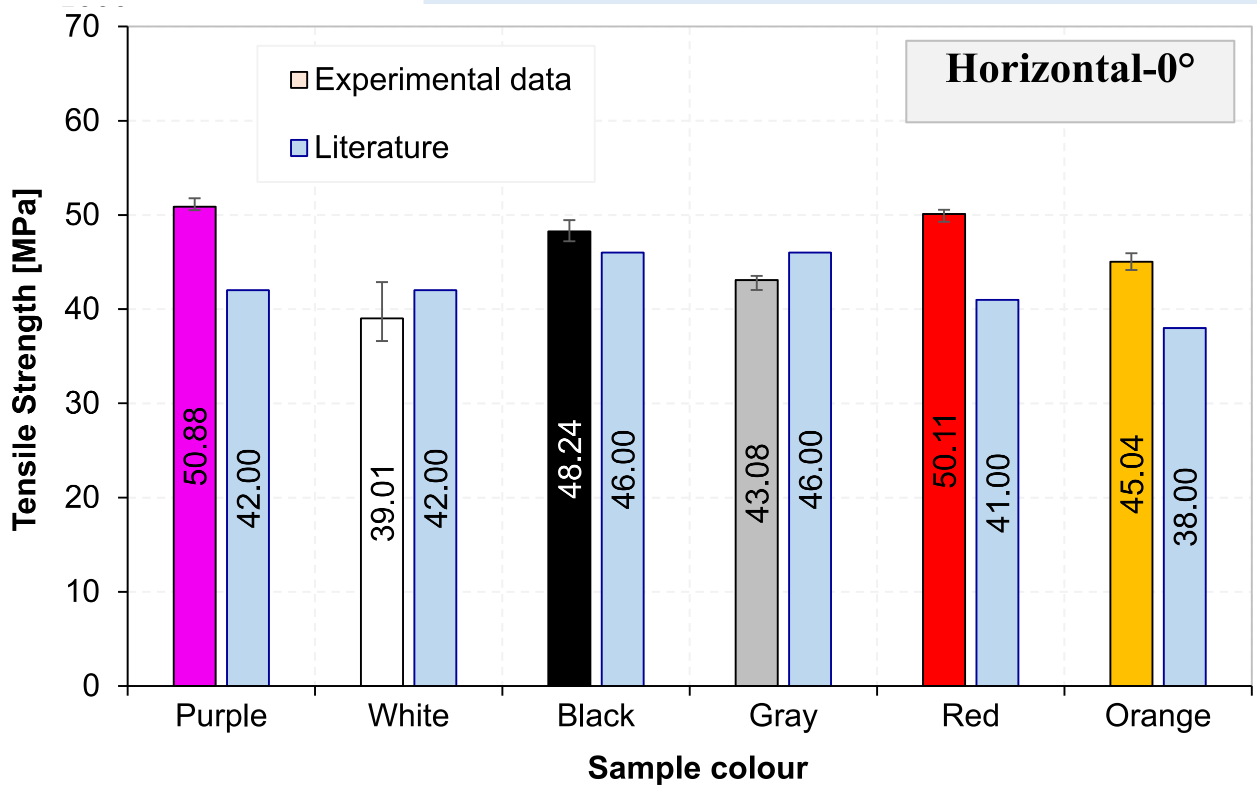


Tensile strength

Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

➢ **Influence of filament color**

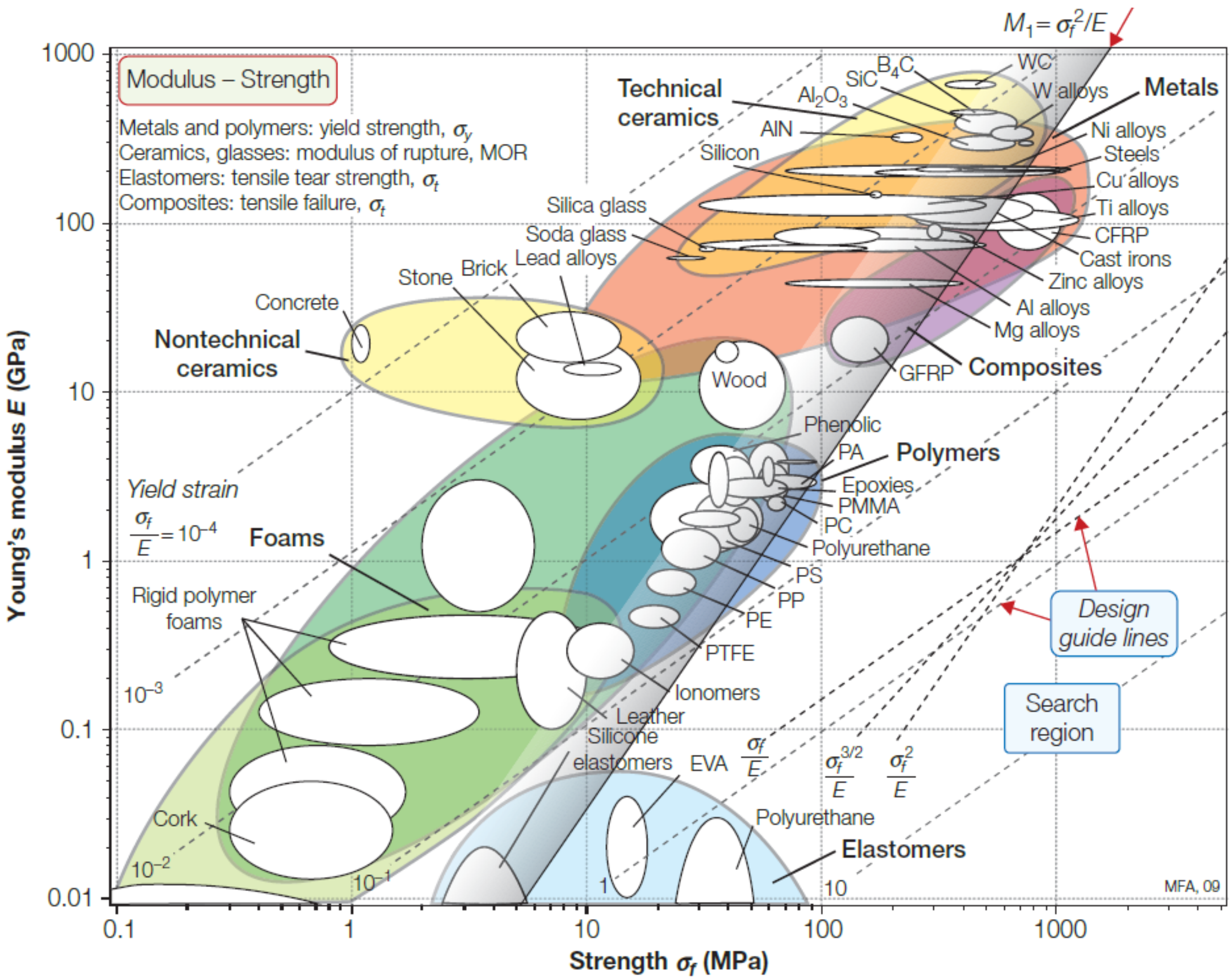
A. Pandzic, D. Hodzic, A. Milovanovic, **INFLUENCE OF MATERIAL COLOUR ON MECHANICAL PROPERTIES OF PLA MATERIAL IN FDM TECHNOLOGY** , Proceedings of the 30th DAAAM International Symposium, 2019



Tensile strength

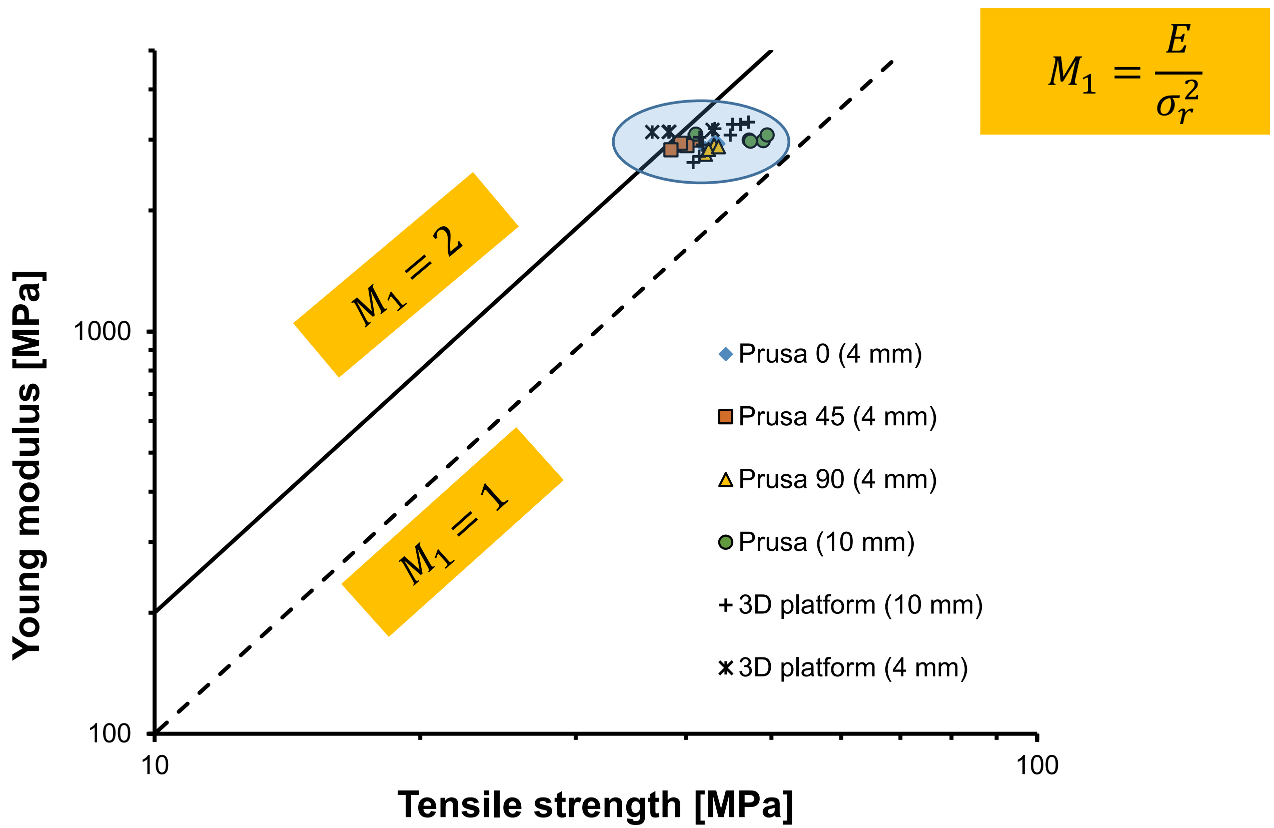
Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

- **Ashby selection diagram**



Determination of tensile properties of plastics, [ASTM D638, ISO 527-2]

➢ **Ashby selection diagram**



There are no particular standards for AM materials!

Designation: D5045 – 14

Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials[1]

This standard is issued under the fixed designation D5045; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 These test methods are designed to characterize the toughness of plastics in terms of the critical-stress-intensity factor, K_{Ic}, and the energy per unit area of crack surface or critical strain energy release rate, G_{Ic}, at fracture initiation.

1.2 Two testing geometries are covered by these test methods, single-edge-notch bending (SENB) and compact tension (CT).

1.3 The scheme used assumes linear elastic behavior of the cracked specimen, so certain restrictions on linearity of the load-displacement diagram are imposed.

1.4 A state-of-plane strain at the crack tip is required. Specimen thickness must be sufficient to ensure this stress state.

priate safety and health practices and determine the applicability of regulatory limitations prior to use.

NOTE 1—This standard and ISO 13586 address the same subject matter, but differ in technical content.

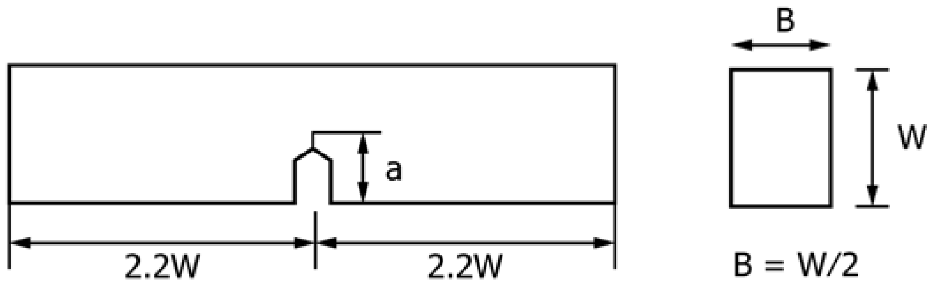
2. Referenced Documents

2.1 *ASTM Standards:*[2]

D638 Test Method for Tensile Properties of Plastics
D4000 Classification System for Specifying Plastic Materials
E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

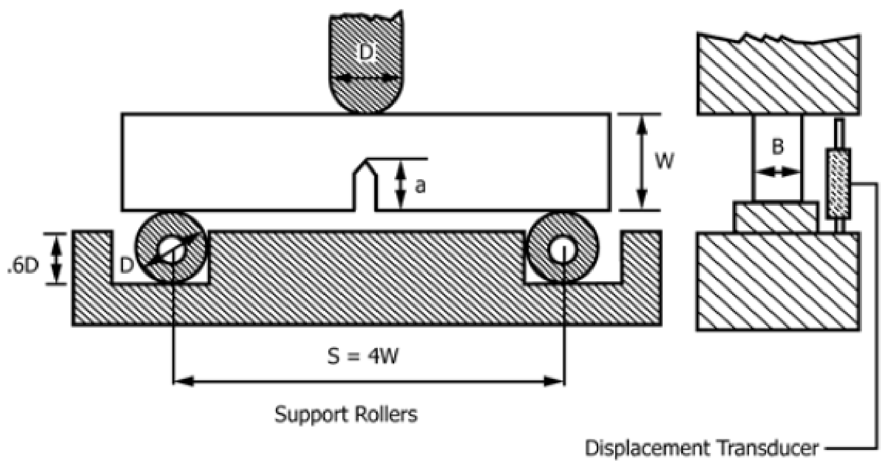
Determination of fracture toughness of plastics, [ASTM D5045]

- **Single Edge Notched Specimen**



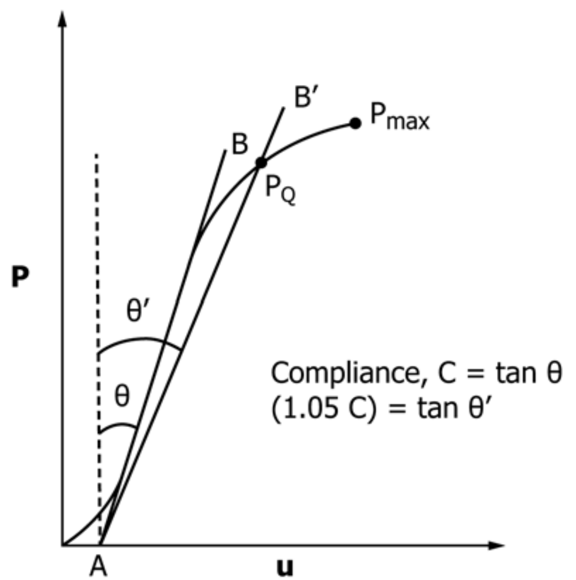
B = 6 mm
W = 12 mm
a = 6 mm
S = 48 mm

- **Loaded in Three point bending**



Determination of fracture toughness of plastics, [ASTM D5045]

- **Load – displacement curve**



Calculation of fracture toughness

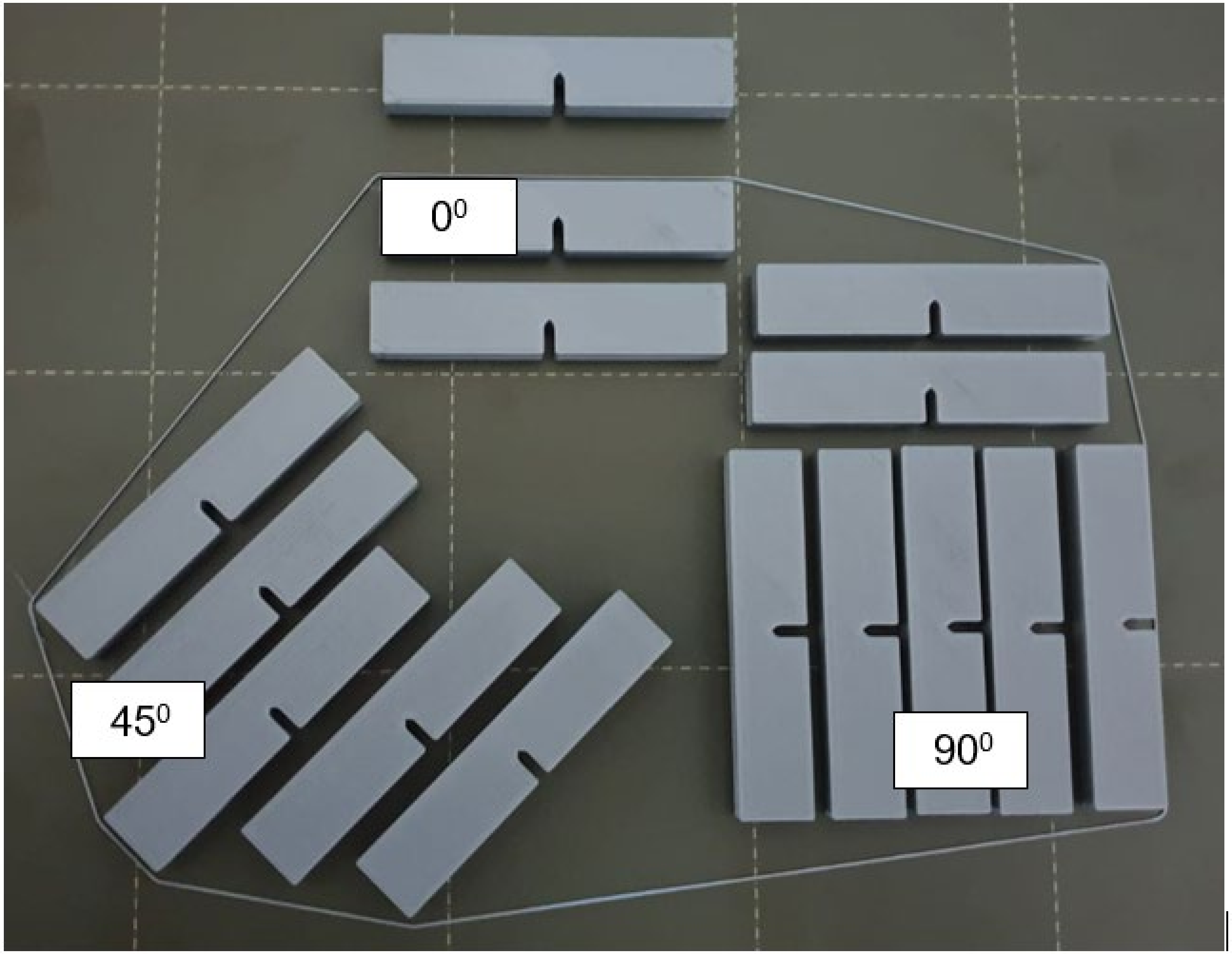
$$K_Q = \frac{P_Q}{B \cdot W^{1/2}} \cdot f_I\left(\frac{a}{w}\right)$$

$$f_I\left(\frac{a}{W}\right) = 6\left(\frac{a}{W}\right)^{1/2} \frac{1.999-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left(2.15-3.93\left(\frac{a}{W}\right)+2.7\left(\frac{a}{W}\right)^2\right)}{\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}$$

- **Validity criteria (plain strain condition)**

$$B, a, (W-a) > 2.5\left(\frac{K_Q}{\sigma_y}\right)^2$$

Printed specimens



Determination of fracture toughness of plastics, [ASTM D5045]

- **Results on fracture toughness**

PLA	Grey	27/01/2021
Tensile test		
Loading speed	2 mm/min	

Specimen ID	Thickness	Width	Crack length	Adimansional function		Max load	Fracture toughness KQ	
	B [mm]	B [mm]	a [mm]	a/W [-]	fI (a/W) [-]	PQ [N]	KQ [MPa mm$^{0.5}$]	KQ [MPa m$^{0.5}$]
0	5.99	12.19	6.00	0.49	10.39	187	92.92	2.94
45	6.01	12.14	6.00	0.49	10.46	213	106.37	3.36
90	6.00	12.07	6.00	0.50	10.55	229	115.93	3.67

$$f_I\left(\frac{a}{W}\right) = 6\left(\frac{a}{W}\right)^{1/2} \frac{1.99-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left(2.15-3.93\left(\frac{a}{W}\right)+2.7\left(\frac{a}{W}\right)^2\right)}{\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}$$

$$K_Q = \frac{P_Q}{B \cdot W^{1/2}} \cdot f_I\left(\frac{a}{W}\right)$$

Printed components (ABS medical)