4a test packages

thermoplastic materials
setups & measurement definition

IMPETUS
VALIMAT

excellence in
plastics & simulation
testing equipment
lightweight products

Quality Preamble

To address the need for traceability of the results, the measuring equipment will be calibrated at fixed intervals or verified before use against international or national measurement standards.

Thus, there is traceability to international or national measurement standards ensured. If such measuring standards does not exist, the basis for the calibration or verification must be recorded.

Certificates

- **EN ISO 9001:2015**
- **EN ISO 14001:2015**
- **TISAX**

Content

1 VALIMAT® – from test to material card

VALIMAT® is the software solution that combines a clever storage system with the ability to generate and fully automated fit measurements from different tests to a material model in the most common solvers. Base of all material models is the 3-point bending test. Conducting it at different velocities a simple elastic-viscoplastic material card is modelled. This model can then be validated on different complexity levels of tests and expanded to more sophisticated material models. Figure 1 shows the common characterization pyramid schematic.

All data is merged in a single database and is arranged under general information, test setup, test specimen data and evaluation setting for quick and easy accessibility. It does not alter original test data which is stored in subfolders for each test run individually (\...\curvestore\yymmdd_testno).
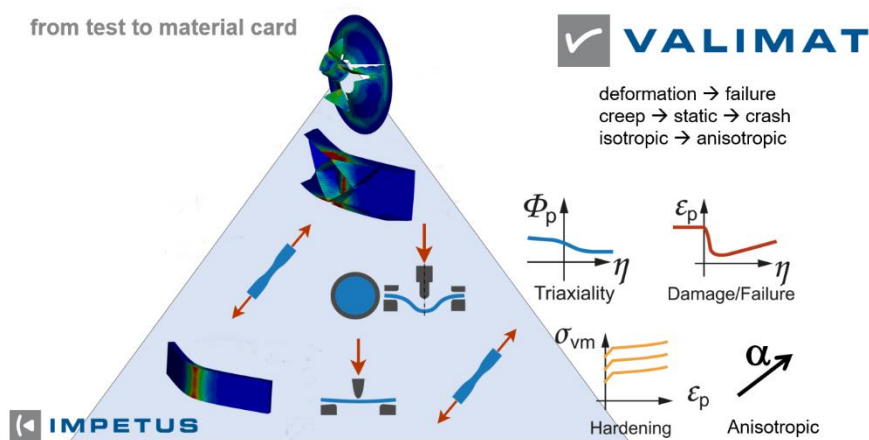
Figure 1: Characterization pyramid for VALIMAT®; from basic characterization up to final component validation

1.1   Test packages overview

All tests are optimized for plastics and plastic composites, which are applied in components that typically deal with complex dynamic and/or static load cases under various temperatures, requiring simulation pre-application. This document specifies on how data is generated for the creation of material cards and sets a standard for all mentioned methods. An overview of the different material packages at room temperature is shown in Figure 2 and Figure 3. In general, 5 repetitions per test setup are considered for all test packages except the BASIC package, where a reduced test scope of 3 repetitions per test setup are considered.

Figure 2: Test plan overview for the isoP material packages at room temperature (23°C)

Figure 3: Test plan overview for the frP material packages at room temperature (23°C)

isoP

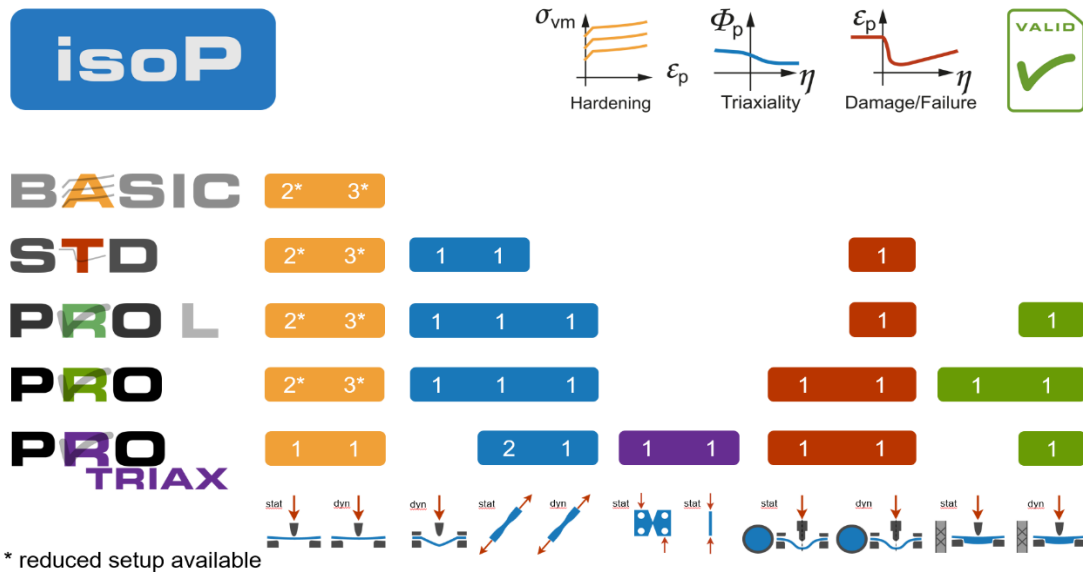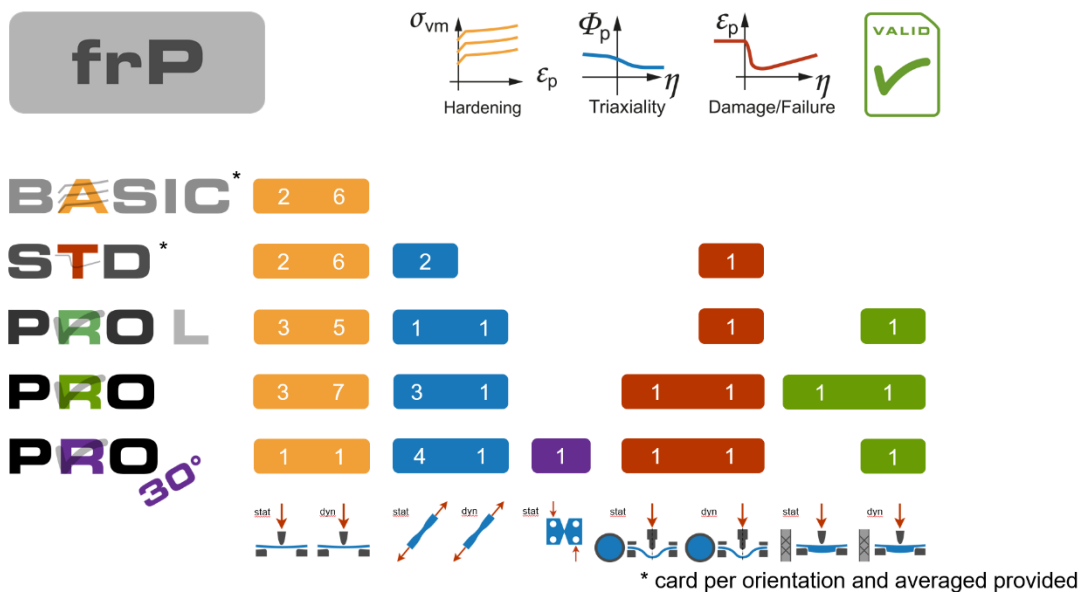| Temp (°C)	Test method	Specimen type	Orientation	Velocity (m/s)	basic	standard	Pro L	Pro	Pro Triax
23	3-Point Bending	BE-V2 50x10x2 mm	0	0.0001	✔	✔	✔	✔	-
		BE-V2 50x10x2 mm	0	0.001	✔	✔	✔	✔	✔ +90°
		BE-V2 50x10x2 mm	0	1	✔	✔	✔	✔	-
		BE-V2 50x10x2 mm	0	2.5	✔	✔	✔	✔	✔ +90°
		BE-V1 40x10x2 mm	0	4	✔	✔	✔	✔	-
	Tension	UT-Typ3	0	0.001	-	✔	✔	✔	✔ +90°
		UT-Typ3	0	3	-	-	✔	✔	✔
	Cyclic tensile	UT-Typ3	0	0.0001	-	-	-	-	✔
	Tension bending	TBE-V1 80x10x2 mm	0	3	-	✔	✔	✔	-
	Puncture test	PT-STAT-V1 80x80x2 mm	0	0.001	-	-	-	✔	✔
		PT-DYN-V1 120x80x2 mm	0	3	-	✔	✔	✔	✔
	Shear test	SH-V1 Butterfly	0	0.0001	-	-	-	-	✔
	Compression test	CT-Celanese 50x10x2 mm	0	0.0001	-	-	-	-	✔
	Component test	XX-Rib		0.001	-	-	-	✔	-
		XX-Rib		3	-	-	✔	✔	✔
				Tests in total	15	40	50	60	65
-35	3-Point Bending	BE-V2 50x10x2 mm	0	0.0001	-	✔	✔	✔	-
		BE-V2 50x10x2 mm	0	0.001	-	✔	✔	✔	✔
		BE-V2 50x10x2 mm	0	1	-	✔	✔	✔	-
		BE-V2 50x10x2 mm	0	2.5	-	✔	-	-	✔
		BE-V1 40x10x2 mm	0	4	-	-	✔	✔	-
	Tension	UT-Typ3	0	0.001	-	✔	✔	✔	✔
		UT-Typ3	0	3	-	-	✔	✔	✔
	Puncture test	PT-STAT-V1 80x80x2 mm	0	0.001	-	-	-	✔	-
		PT-DYN-V1 120x80x2 mm	0	3	-	✔	✔	✔	✔
	Component test	XX-Rib		0.001	-	-	-	✔	-
		XX-Rib		3	-	-	✔	✔	✔
				Tests in total	-	30	40	50	30
90	3-Point Bending	BE-V2 50x10x2 mm	0	0.0001	-	✔	✔	✔	-
		BE-V2 50x10x2 mm	0	0.001	-	✔	✔	✔	✔
		BE-V2 50x10x2 mm	0	1	-	✔	✔	✔	-
		BE-V2 50x10x2 mm	0	2.5	-	✔	-	-	✔
		BE-V1 40x10x2 mm	0	4	-	-	✔	✔	-
	Tension	UT-Typ3	0	0.001	-	✔	✔	✔	✔
		UT-Typ3	0	3	-	-	✔	✔	✔
	Puncture test	PT-STAT-V1 80x80x2 mm	0	0.001	-	-	-	✔	-
		PT-DYN-V1 120x80x2 mm	0	3	-	✔	✔	✔	✔
	Component test	XX-Rib		0.001	-	-	-	✔	-
		XX-Rib		3	-	-	✔	✔	✔
				Tests in total	-	30	40	50	30

Table 1: Detailed overview of the test plan with specimen type, typical test velocities (may vary on a material basis to ensure failure) and temperatures for the isoP material packages

frP

Temp (°C)	Test method	Specimen type	Orientation	Velocity (m/s)	basic	standard	Pro L	Pro	Pro 30°
23	3-Point Bending	BE-V2 50x10x2 mm	0° & 90°	0.0001	-	-	-	-	-
				0.001	✓	✓		✓ +30°	
				1	✓	✓	-	✓	-
				2.5	✓	✓		✓ +30°	
		BE-V1 40x10x2 mm		4	✓	✓	✓	✓	-
	Tension	UT-Typ3	0° & 90°	0.0001	-	✓	30° only	✓ +30°	
			30°	3	-	-	✓	✓	✓
	Cyclic tensile			0.0001	-	-	-	-	✓
	Puncture test	PT-STAT-V1 80x80x2 mm		0.001	-	-	-	✓	✓
		PT-DYN-V1 120x80x2 mm		3	-	✓	✓	✓	✓
	Shear test	SH-V1 Butterfly	30°	0.0001	-	-	-	-	✓
	Component test	XX-Rib		0.001	-	-	-	✓	-
				3	-	-	✓	✓	✓
				Tests in total	24	55	60	90	75
-35	3-Point Bending	BE-V2 50x10x2 mm	0° & 90°	0.0001	-	-	-	-	-
				0.001	-	✓		✓ +30°	30° only
				1	-	✓	-	✓	-
				2.5	-	✓		✓ +30°	30° only
		BE-V1 40x10x2 mm		4	-	✓	✓	✓	-
	Tension	UT-Typ3	0° & 90°	0.0001	-	-	30° only	✓ +30°	30° only
			30°	3	-	-	✓	✓	✓
	Puncture test	PT-STAT-V1 80x80x2 mm		0.001	-	-	-	✓	-
		PT-DYN-V1 120x80x2 mm		3	-	✓	✓	✓	✓
	Component test	XX-Rib		0.001	-	-	-	✓	-
				3	-	-	✓	✓	✓
				Tests in total	-	45	60	90	30
90	3-Point Bending	BE-V2 50x10x2 mm	0° & 90°	0.0001	-	-	-	-	-
				0.001	-	✓		✓ +30°	30° only
				1	-	✓	-	✓	-
				2.5	-	✓		✓ +30°	30° only
		BE-V1 40x10x2 mm		4	-	✓	✓	✓	-
	Tension	UT-Typ3	0° & 90°	0.0001	-	-	30° only	✓ +30°	30° only
			30°	3	-	-	✓	✓	✓
	Puncture test	PT-STAT-V1 80x80x2 mm		0.001	-	-	-	✓	-
		PT-DYN-V1 120x80x2 mm		3	-	✓	✓	✓	✓
	Component test	XX-Rib		0.001	-	-	-	✓	-
				3	-	-	✓	✓	✓
				Tests in total	-	45	60	90	30

Table 2: Detailed overview of the test plan with specimen type and typical test velocities (may vary on a material basis to ensure failure) for the frP material packages

IN PHYSICS WE TRUST

2 Sampling – general

All standard specimens are generated by further processing of the standardized casting mold for injection molding, henceforth referred to as "4a mold", as shown in Figure 4.
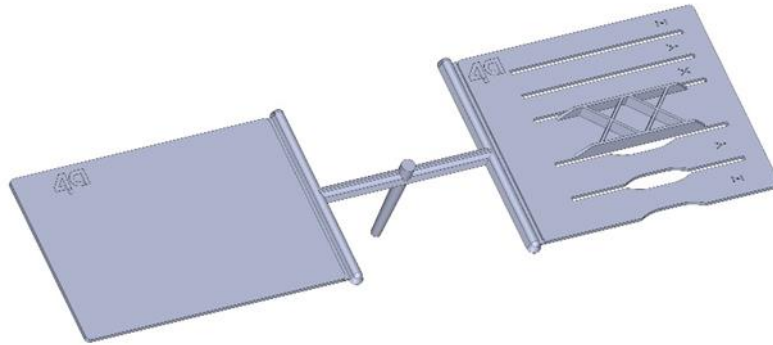

Figure 4: 4a mold

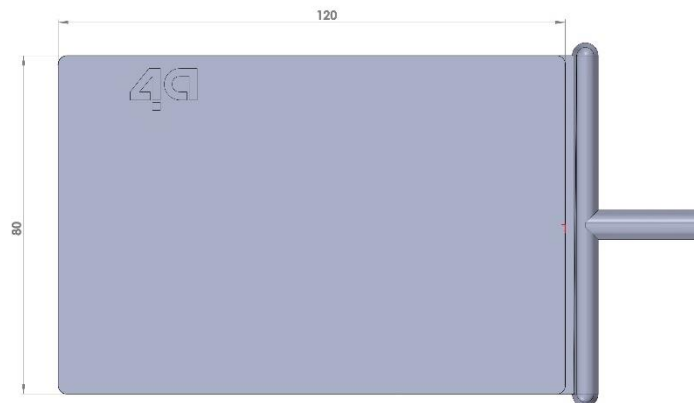It consists of the 120x80x2 plate (Figure 5) and the multi-specimen plate (Figure 6)
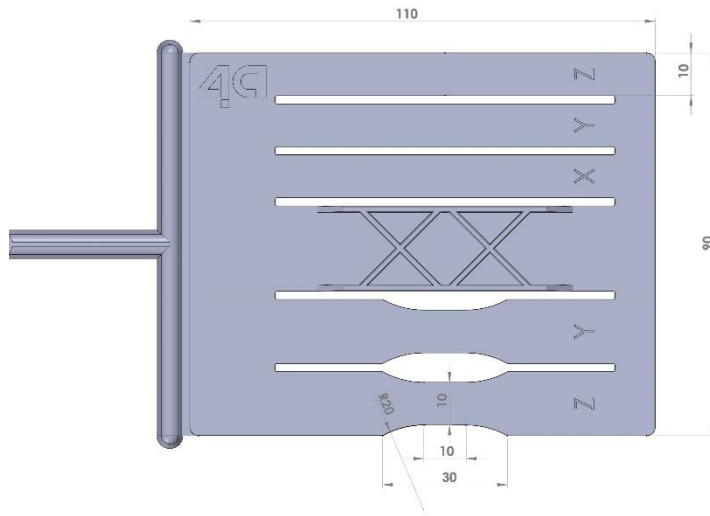

Figure 5: 120x80x2 plate

Figure 6: Multi-specimen plate

To achieve best quality in the production of the samples the injection molding process parameters may vary significantly depending on the material.

The specimens are either directly sawed off the plates or milled out of the 120x80x2 plate.

To achieve different orientations, which results from the injection molding process, the specimens are each taken from defined areas within the 120x80x2 plate. Differentiating between longitudinal – 0° (Figure 7), transversal – 90° (Figure 8), diagonal – 45° (Figure 9) and average – 30° (Figure 10). The name "average" stems from the average mechanical behaviour of 30° oriented fibre reinforced plastics.

The designation of the specimens follows a system that enable unique numbering. The denomination consists of the individual mold number, consecutively defined during the injection mold process, a letter for its orientation and, if multiple specimens are taken from a plate, the number of the positioning on the plate as shown on Figure 7 and Figure 8. Example: 3 specimens, 90° oriented, milled out of plate No. 50 would be named: 50_Q1, 50_Q2 and 50_Q3. 50_Q1 being the closest to the injection section, 50_Q3 the furthest. The specific positioning may cause different, but reproduceable, mechanical behaviour.
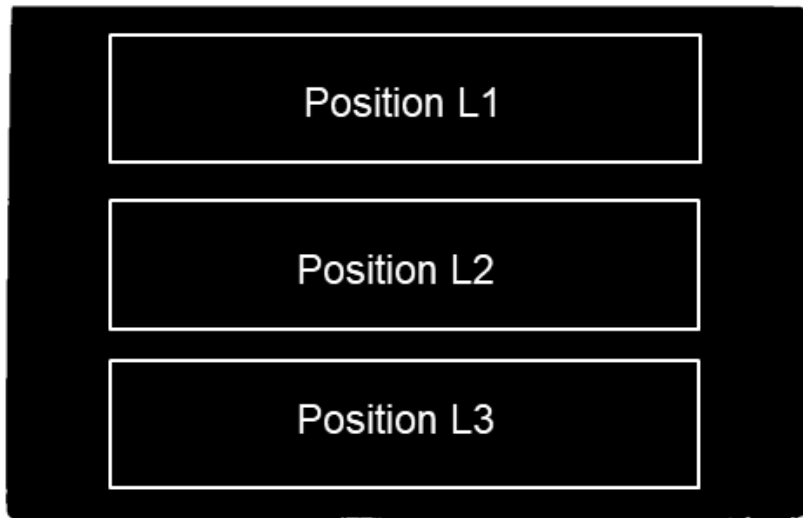
L - longitudinal

Figure 7: Areas of the 120x80x2 plate for milling 0° specimen, each square measure at 90x20. The arrow indicates the flow direction
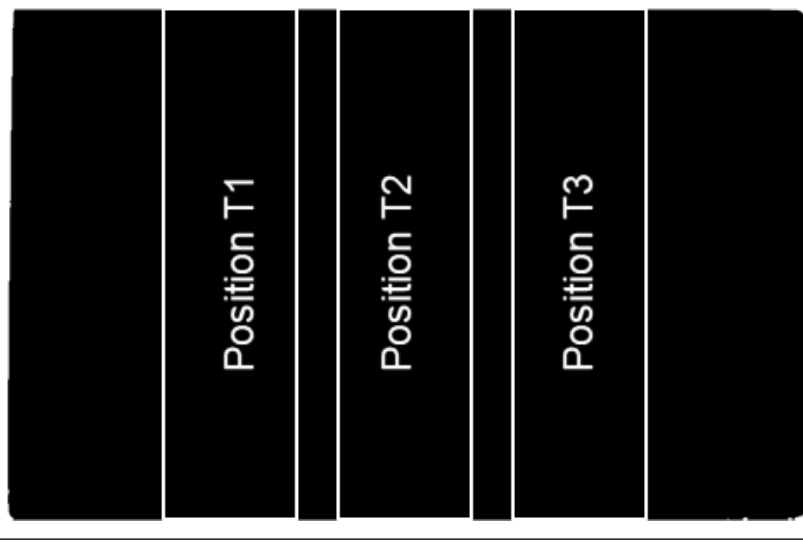
T - transversal

Figure 8: Areas of the 120x80x2 plate for milling 90° specimen, each square measure at 80x20. The arrow indicates the flow direction
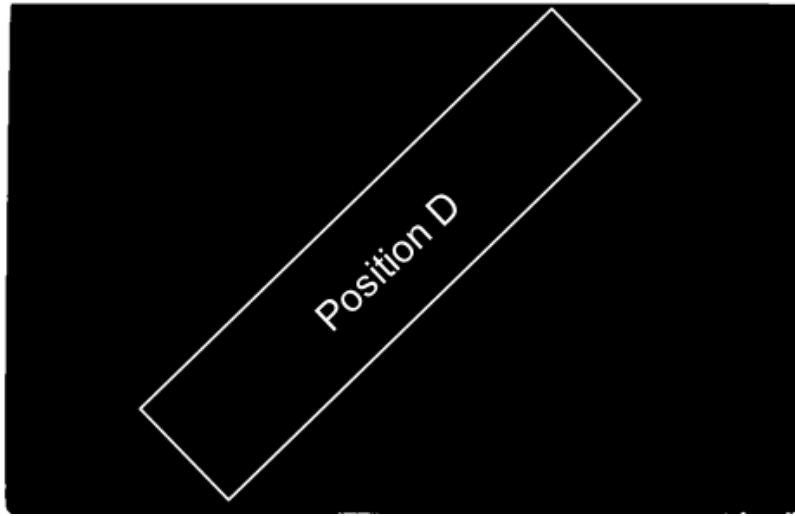
D - diagonal

Figure 9: Area of the 120x80x2 plate for milling 45° specimen, the square measures at 90x20. The arrow indicates the flow direction
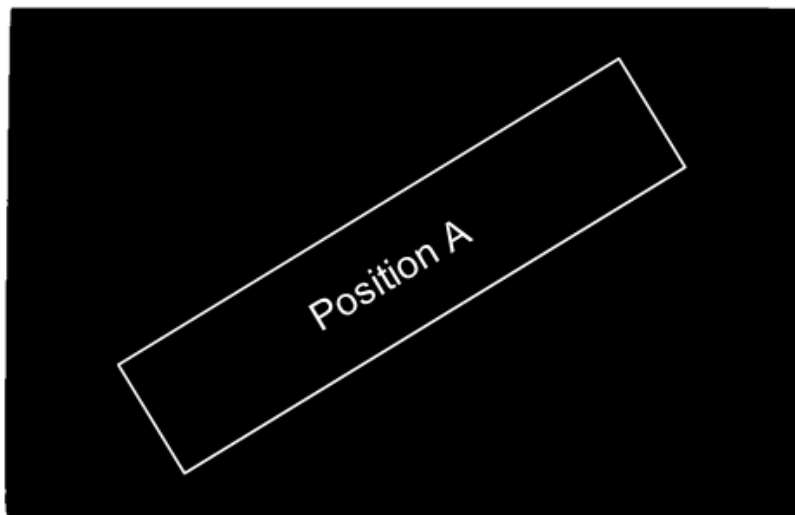
A - average

Figure 10: Area of the 120x80x2 plate for milling 30° specimen, the square measures at 90x20. The arrow indicates the flow direction

All processed specimen edges are polished/grinded with a 600-grit sandpaper to prepare them for the material tests. Specimens are visually controlled and are discarded if they show any flaws on the surface, such as pits, scratches or shrink marks.

For maximum geometrical deviations look at 11.1.1.

The milling process may introduce slight defects and heats the specimen to a certain extent. Furthermore, molded specimens are prone to show higher fibre orientations than the milled counterparts. This could result in small changes to mechanical behaviour, which is to be regarded whilst testing milled and molded specimen of the same orientation.

Weight of the specimens is documented with a digital micro scale (specified in 11.2).

3   Specimen conditioning

For measurements at room temperature all specimens are kept at least 24h under standardized climate (23°C, 50% RH) conditions as defined in ISO 291.

Polymers that show a strong dependency on moisture conditions are handled according to ISO 1110.

If not specified otherwise, standard high and low testing temperatures are +80°C and -30°C. Since static and dynamic measurements are conducted on different machines, different procedures are defined as following for high and low temperature measurements (HT, LT):

3.1   Static measurements at high or low temperatures

The specimens are conditioned for >4h beforehand in a separate furnace or cooling chamber at the exact measuring temperature. HT specimens will not be kept longer than 6h on testing temperatures. For keeping the specimen on temperature during the test, a thermostatic chamber (Shimadzu TCE-N300) is applied to the universal testing machine, as depicted on Figure 11. It uses liquid N_2 for cooling and a thermoelectric heating system. The thermostatic chamber is able to keep set temperature accurate to ±1.5°C of its range from -70°C to +250°C.

Figure 11: Static measurements at high or low temperature

3.2 Dynamic measurements at high or low temperatures

It is not possible to heat/cool the specimen during the dynamic tests itself, hence it is necessary to swiftly execute the measurement. Since dynamic measurements have shorter test periods the influence surroundings at room temperature is limited. The operator targets trial periods of 15s. To ensure those short test periods, different measures are taken depending on the test.

For tempered 3-Point-Bending a temperature magazine is used. The magazine is made of aluminium and holds place for twenty specimens. The magazine is loaded with the specimens and heated/cooled to desired temperature >4h beforehand. HT specimens will not be kept longer than 6h on testing temperatures. After tempering, the magazine is isolated to keep consistent temperature. The insulation magazine is illustrated on Figure 12. To exclude possible inaccuracies in temperature by the tester touching the specimen, a plastic tweezer is used to position the specimen on the counter bearing.

Figure 12: 4a insulation magazine

Tempered dynamic puncture tests and tensile tests are conducted by tempering the already clamped specimen in an external furnace/cooling chamber, which are set 4°C above (HT) / below (LT) desired testing temperature. The clamped specimen is then put directly into the machine.

4   Machines used

4.1   4a IMPETUS® pendulum

All dynamic tests are executed on a 4a IMPETUS® pendulum, using different setups described for each method. It consists of an optimized swinging arm made of CFRP and aluminium alloy, an electro-magnetic spring-loaded single disc brake to setup and release the falling position of the swing hammer. To introduce different impact energies according to the test requirements, it is possible to choose between a 25J max. arm and a 50J max. arm which can be equipped with additional weight. An angle sensor (specified in 11.2) located on the pendulums pivot is used to set the position of the pendulum in accordance with the testing velocity and to measure the exact velocity at the impact. It utilizes temperature and humidity sensors to record possible deviations from standard climate. A variety of different accelerations sensors (specified in 11.2) are available to fit the sensors specific range on estimated load cases. Data acquisition is limited by a maximum sampling rate of 1MHz using multichannel (2 MHz single channel).

4.2   Shimadzu AGS-X, AG-X

Static tests are executed on the universal testing machines "AG-X" and "AGS-X" by Shimadzu, again using different setups described for each test. Various load cells according to ISO 7500 are utilized for force measurement, an optical encoder is used to determine crosshead position for displacement and velocity evaluations.

5   3-Point-Bending (3PB)

5.1   Specimen geometry

For 3PB tests there are six cuboid geometries available, which are optimized for strain rate dependant evaluation, whilst limiting swinging phenomena in dynamic testing:

- IMPETUS®-BE-V1, 40x10x2 (standard)
- IMPETUS®-BE-V2, 50x10x2 (standard)
- IMPETUS®-BE-V3, 60x10x3 (optional)
- IMPETUS®-BE-V4, 60x20x3 (used for laminates)
- IMPETUS®-TBE-V1, 80x10x2 (tension bending)
- IMPETUS®-TBE-V2, 100x10x2 (tension bending)

If not specified otherwise the injection molded specimens are used, which are sawed off directly from the multi-specimen plate, as seen in Figure 13.
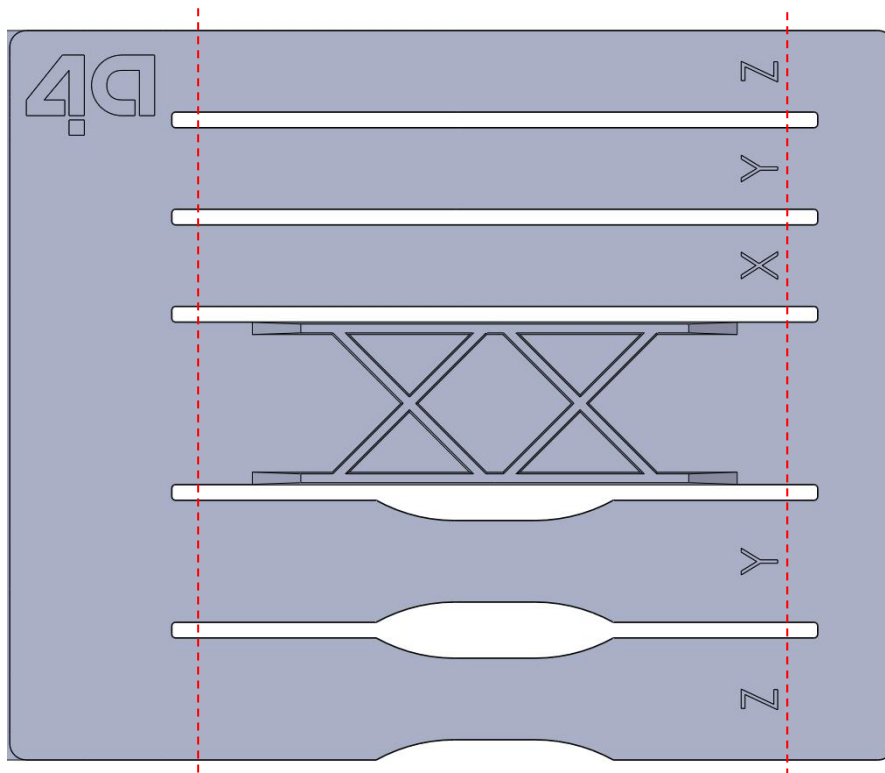
Figure 13: Standard sampling for 3PB, denomination as depicted

5.2   Static testing

5.2.1   Setup

The static 3PB test is conducted on a universal testing machine (Shimadzu AGS-X). The radius of the fin is 2mm. The counter-bearing has a 2mm support radius, and can be set to different supporting distances, in accordance with different specimen geometries. The fin is connected to a 500N load cell (specified in 11.2). The setup is illustrated in Figure 14.
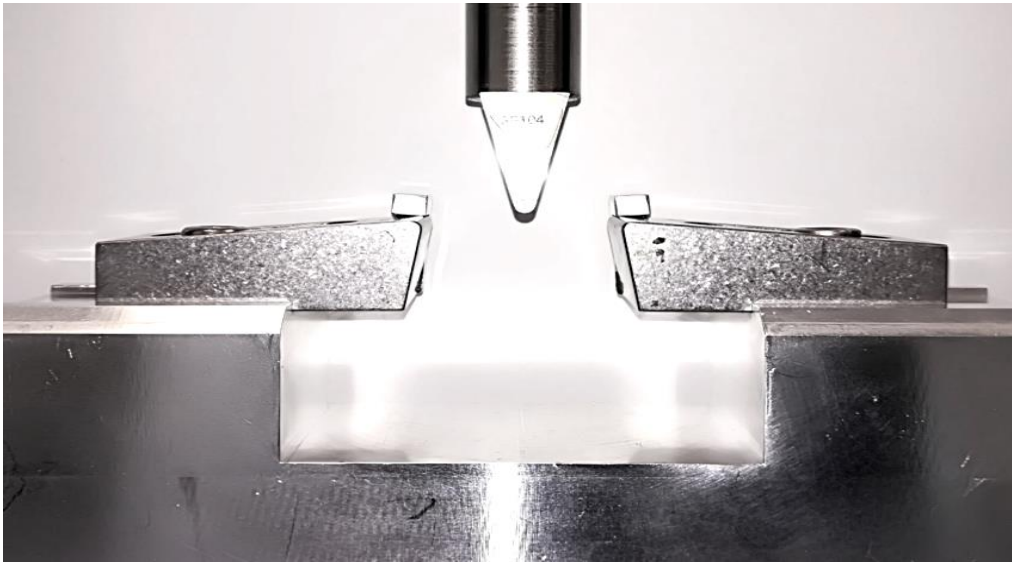
Figure 14: Static 3PB setup

To guide the tester during the central placement of the specimen, a magnetic L-shaped support element is used as shown Figure 15.
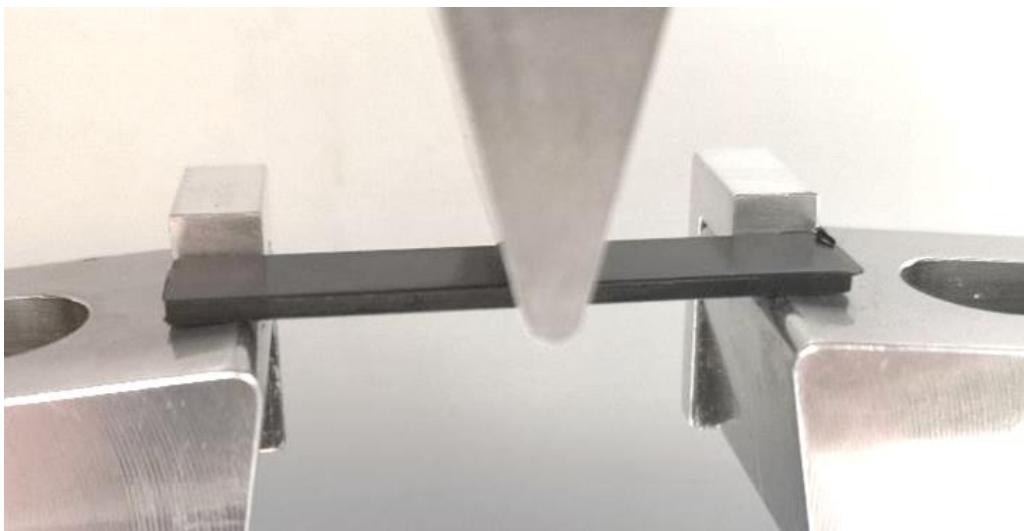
Figure 15: Placement of the specimen

5.2.2   Measurement and evaluation method

Table 3 and Table 4 illustrate different starting strain rates ἑ* resulting from different geometries and different testing velocities used for carrying out the static 3PB test. Figure 16 shows the relevant specimen measurements used in Table 3 Table 3: Testing parameters 3PB - 2mm thicknessand Table 4.

Test-Setup	v_0 [m/s]	l_w [mm]	b [mm]	t [mm]	l [mm]	$\acute{\varepsilon}$ * [1/s]
stat_low	0.0001	40	10	2	50	0.00075
stat_high	0.001	40	10	2	50	0.0074

Table 3: Testing parameters 3PB - 2mm thickness

Test-Setup	v_0 [m/s]	l_w [mm]	b [mm]	t [mm]	l [mm]	$\acute{\varepsilon}$ * [1/s]
stat_low	0.0001	50	10	3	60	0.0007
stat_high	0.001	50	10	3	60	0.0072

Table 4: Testing parameters 3PB - 3mm thickness
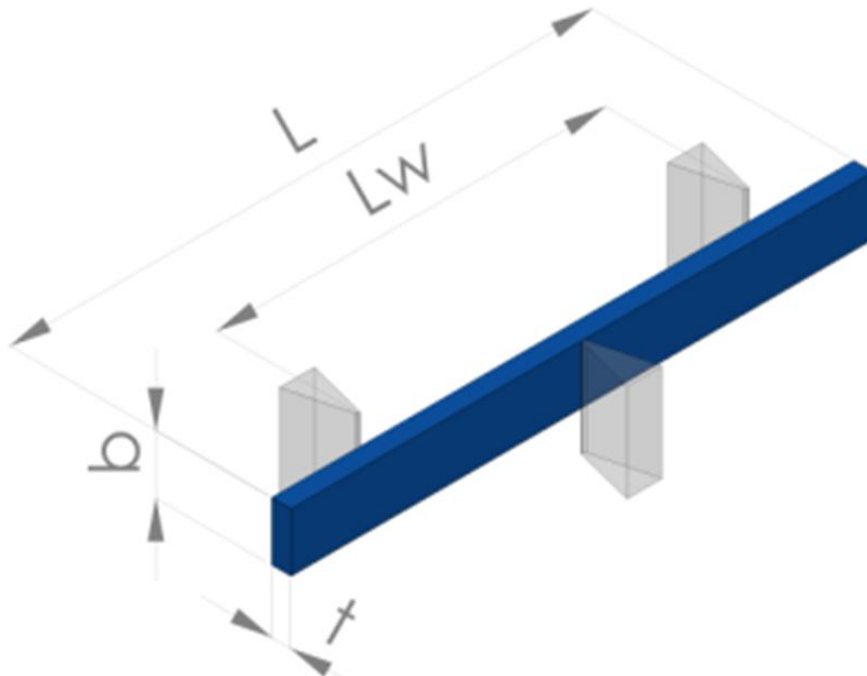
Figure 16: Relevant specimen measurements for testing

Force is measured directly via the load cell. Displacement is measured via the crosshead position. A typical result is displayed in Figure 17.
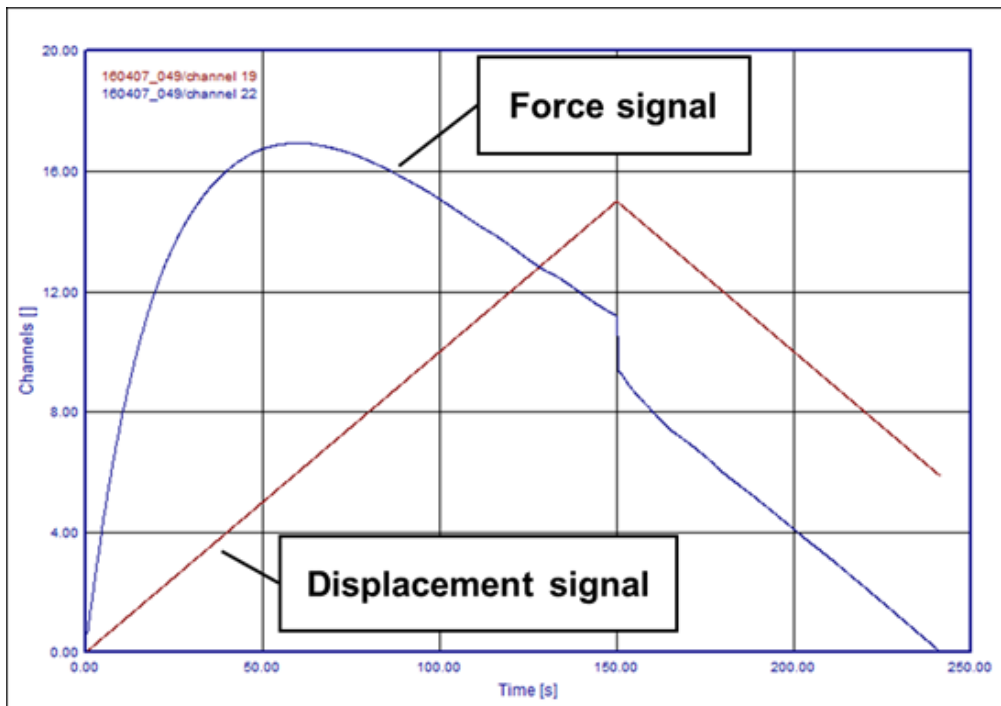

Figure 17: Example results for force and displacement signals of a static 3PB test

Based on the bending beam theory (assumption: Bernoulli Hypothesis, linear elastic) the outer-fibre stress σ, strain ε and strain rate $\dot{\varepsilon}$ can be calculated, as shown in (1), (2) and (3).

$$\sigma = \frac{3 \cdot l_w \cdot F}{2 \cdot b \cdot t^2} \tag{1}$$

$$\varepsilon = \frac{6 \cdot t \cdot s}{l_w{}^2} \tag{2}$$

$$\dot{\varepsilon} = \frac{6 \cdot t \cdot v}{l_w{}^2} \tag{3}$$

l_w ... $distance\ of\ support\ span\ (gauge)$
t ... $specimen\ thickness$
b ... $specimen\ width$
s ... $displacement$
v ... $velocity$
F ... $Force$

Evaluation in ISO 178 is analogue.

5.2.3 Cyclic testing

Cyclic testing is implemented to precisely determine the yield point. The test is carried out on a universal testing machine (Shimadzu AGS-X), using the same measurement methods as described in the static 3PB test. By assessing an earlier conducted static test, the yield limit is evaluated and used for estimating the continuous rising strain applied on the specimen. At least 20 cycles are implemented for this test. Standard testing velocity is 0.1mm/s. A typical result is displayed on Figure 18.
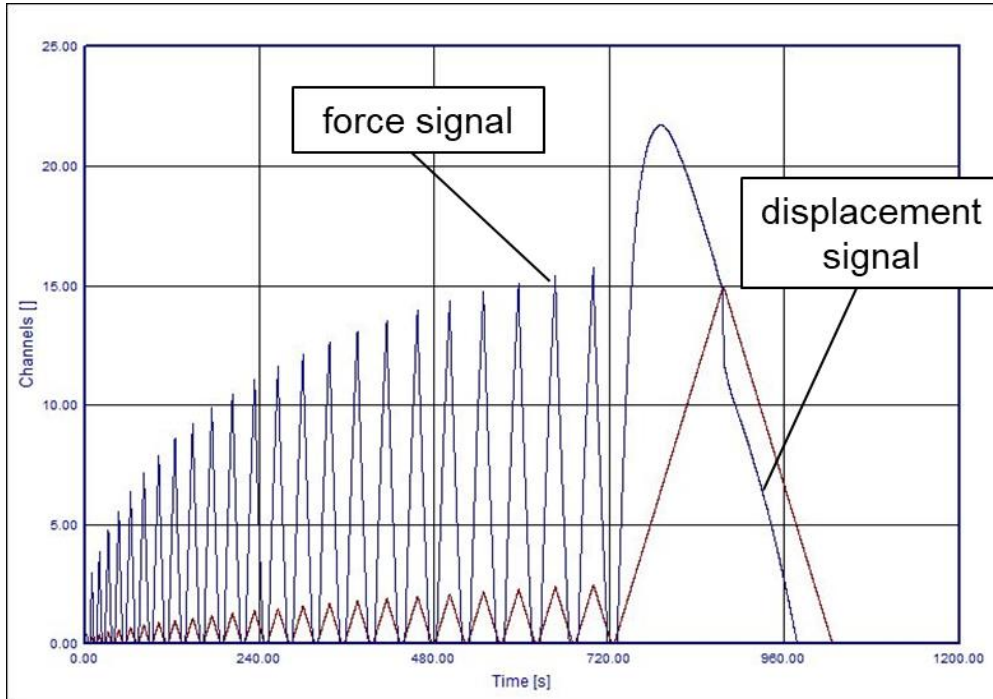
Figure 18: Example result for force and displacement of a cyclic 3PB

The permanent deformation is then evaluated as function of stress. The yield limit is defined by the ascending slope of permanent deformation. As shown on Figure 19.
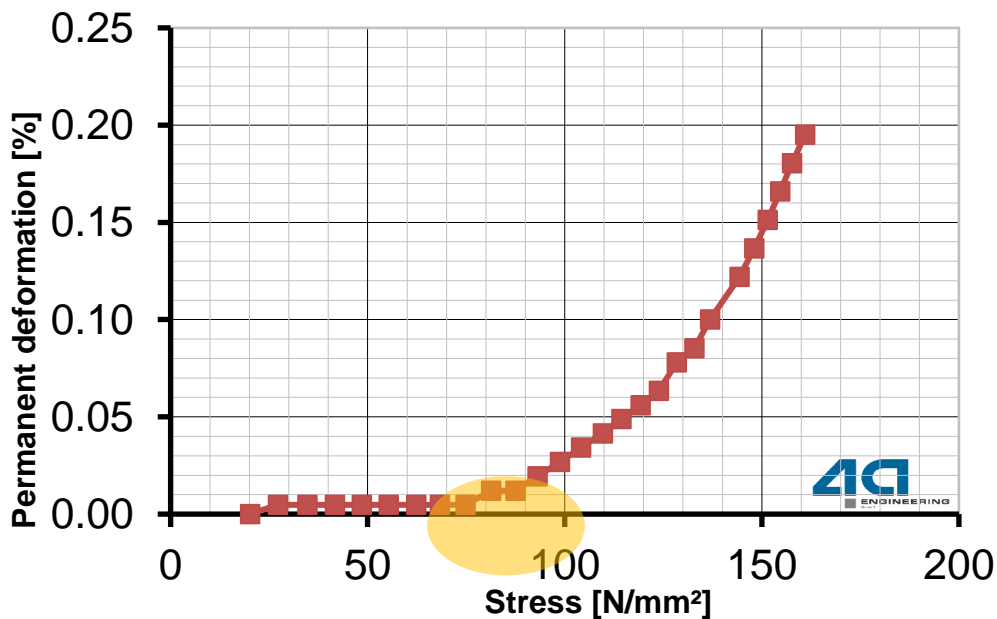
Figure 19: Example evaluation of a cyclic 3PB, the marked area implicates the yield limit

5.3 Dynamic testing

5.3.1 Setup

For the dynamic 3PB test, a 4a IMPETUS® testing pendulum is used with a swing hammer mass of 1580g. Radius of the fin the and the support on the counter bearing are just as in the static test at 2mm. A 25g (g for gravitational constant) acceleration sensor (specified in 11.2) sits on the hammer. The counter bearing is screwed on the machine, a 5g acceleration sensor (specified in 11.2) is applied on it. The test specimen is held in place by magnetic spring elements, which also function as a centring aid. The setup is shown in Figure 20.
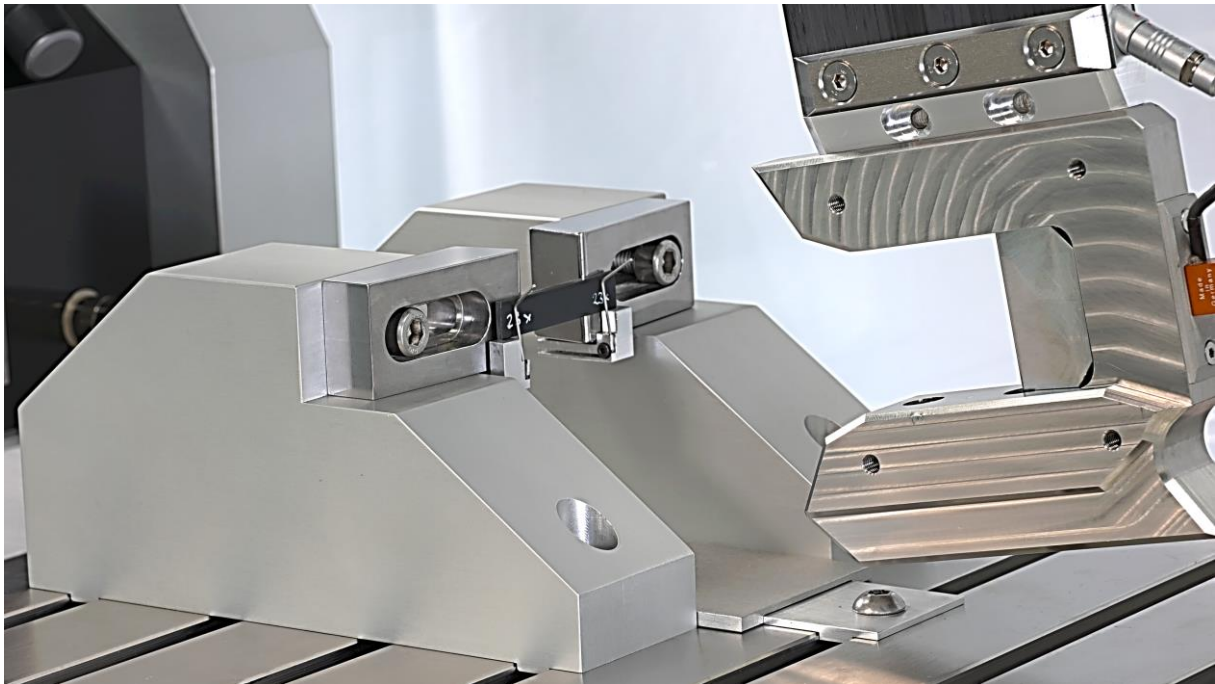
Figure 20: Test setup dynamic 3PB

5.3.2 Measurement and evaluation method

Standard test parameters are displayed in Table 5 and Table 6, illustrating different starting strain rates $\dot{\varepsilon}^*$. Relevant measurements are illustrated on Figure 16.

Test-Setup	v_0 [m/s]	l_w [mm]	$m_{Pendulum}$ [g]	b [mm]	t [mm]	l [mm]	$\dot{\varepsilon}^*$ [1/s]
dyn_low	1	40	1580	10	2	50	7.5
dyn_med	2.5	40	1580	10	2	50	18.75
dyn_high	4	30	1580	10	2	40	53.33

Table 5: Testing parameters dynamic 3PB - 2mm thickness

Test-Setup	v_0 [m/s]	l_w [mm]	$m_{Pendulum}$ [g]	b [mm]	t [mm]	l [mm]	$\acute{\varepsilon}$ * [1/s]
dyn_low	1	50	1580	10	3	60	7.2
dyn_med	2.5	50	1580	10	3	60	18
dyn_high	4	40	1580	10	3	50	45

Table 6: Testing parameters dynamic 3PB - 3mm thickness

Using the acceleration signal of the pendulum and equation (4), the force can be calculated. The velocity can be calculated using the difference of the acceleration signal, as shown in equation (5). The distance can be calculated by either using the acceleration signal or the angle signal as shown in equation (6) and (7) respectively. The bending evaluation is carried out analogue to 5.2.2 (1) (2) (3).

$$F = m_{Pendulum} \cdot a_{Pendulum} \tag{4}$$

$$a_1 = (a_{Pendulum} - a_{0Pendulum}) + (a_{Support} - a_{0Support}) \tag{5}$$

$$v_1 = v_0 + a_1 \cdot (t_1 - t_0) \tag{6}$$

$$s_1 = s_0 + v_1 \cdot (t_1 - t_0) \tag{7}$$

$$s_1 = s_0 + \frac{(\alpha_0 - \alpha_1) \cdot \pi}{180} \cdot L_p \tag{8}$$

A typical result is displayed on Figure 21. Take in regard that the scatter induced in the test curves is due to dynamic swinging phenomena.
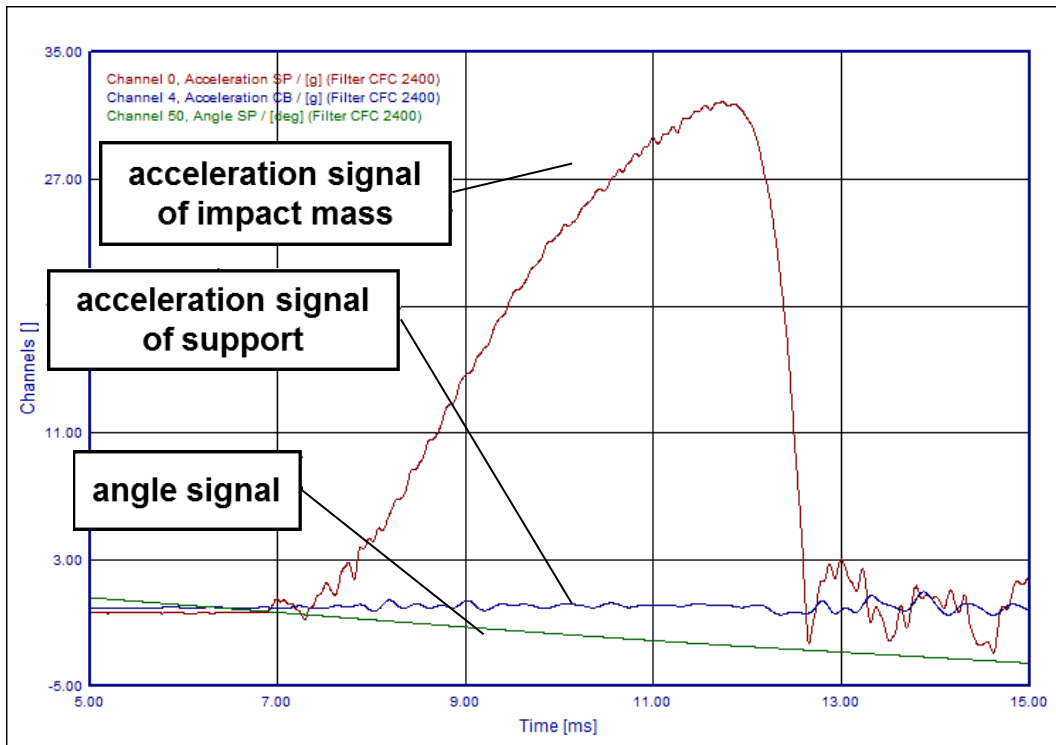
Figure 21: Example results for acceleration and angle of a dynamic 3PB test

5.4 Tension bending (3PBC - 3-Point-bending-clamped)

5.4.1 Setup

The tension bending is also conducted on a 4a IMPETUS® testing pendulum, therefore only dynamic tests are standard. This test is implemented to realize a tension dominated loading situation. Furthermore, significantly higher strains can be achieved compared to the free 3-point-bending. Making it is possible to investigate failure behaviour of ductile materials. With the aid of self-clamping jaws, the reduction in thickness of the test specimens is counteracted. The distance from the support gauge to the clamp is 8 mm, to ensure no bending effects outside the support gauge and to minimize possible shearing effects at the clamped part. The setup is depicted in Figure 22.
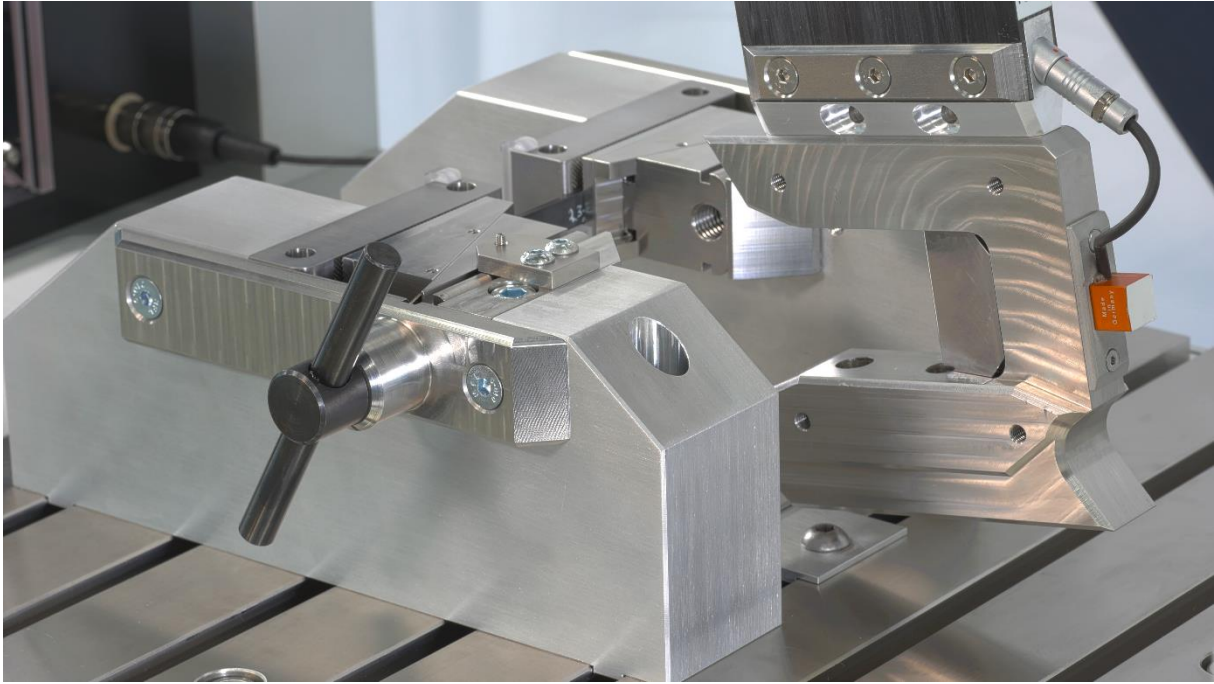
Figure 22: Clamped 3PB setup

5.4.2   Measurement and evaluation method

Standard test parameters are displayed in Table 7. Relevant specimen dimensions are depicted on Figure 23. Measurement methods are equivalent to earlier described 3PB setups.

Test-Setup	v_0 [m/s]	l_w [mm]	$m_{Pendulum}$ [g]	b [mm]	t [mm]	l [mm]
3PBC	3	40	1580	10	2	80

Table 7: Testing parameters dynamic 3PBC
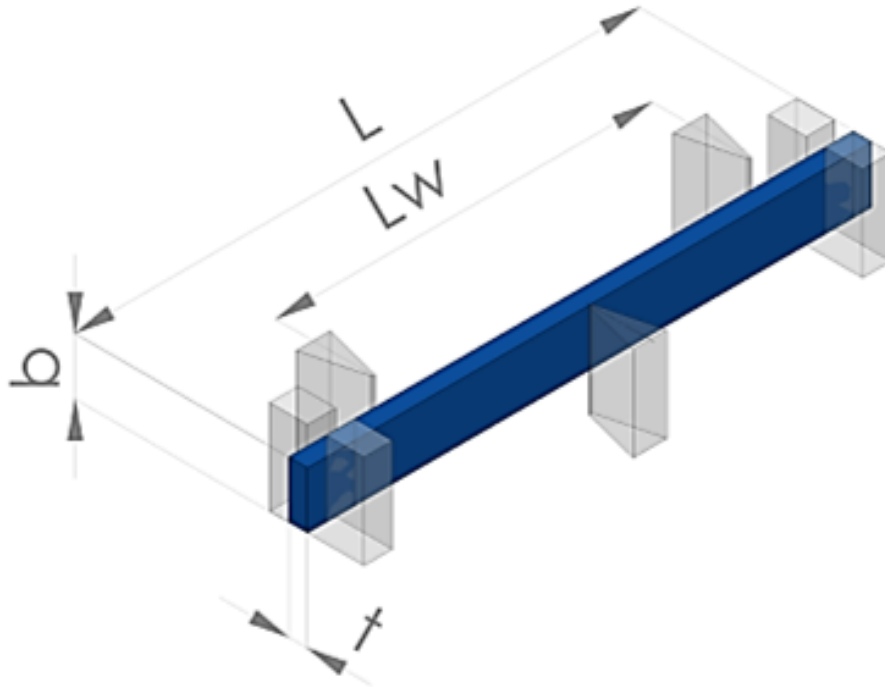
Figure 23: Relevant specimen measurements for testing

6   Tensile test (TT)

6.1   Specimen geometry

Four different specimen geometries are available for tensile tests:

- IMPETUS®-UT-Typ3 (standard, injection molded (isoP) or milled (frP), Figure 24)
- IMPETUS®-UT-Z24 (optional, Figure 25)
- IMPETUS®-UT-Becker (optional, Figure 26)
- IMPETUS®-UT-Junginger (optional, Figure 27)
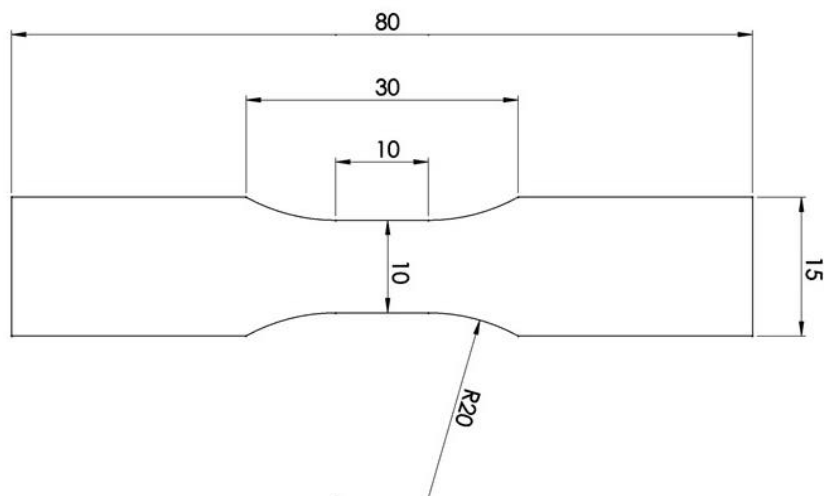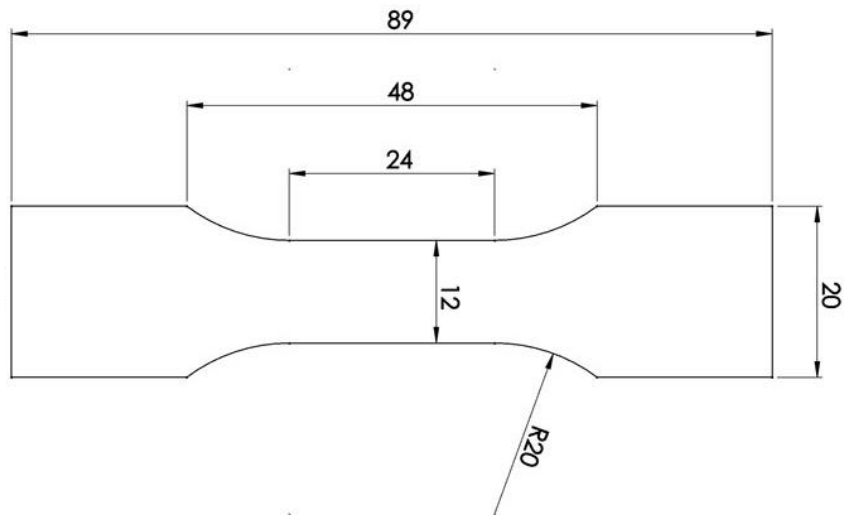

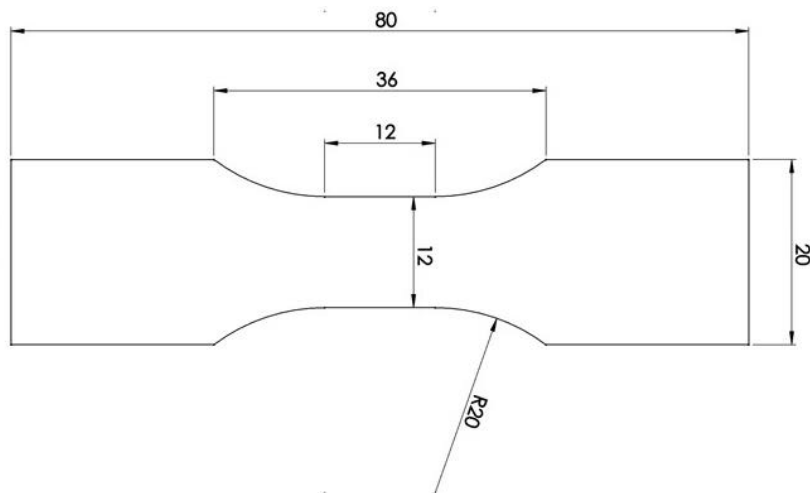*Figure 24: Geometry of IMPETUS®-UT-Type3 specimens*

Figure 25: Geometry of IMPETUS®-UT-Z24 specimens

Figure 26: Geometry of IMPETUS®-UT Becker specimens
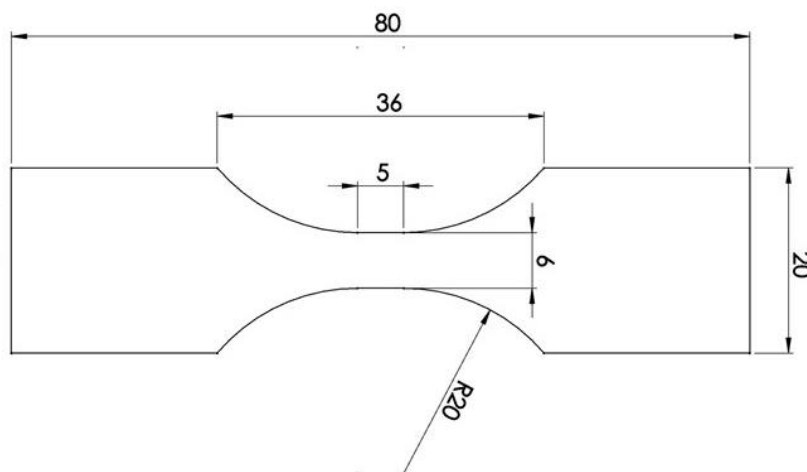
Figure 27: Geometry of IMPETUS®-UT Junginger specimens

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6.2 Static testing

6.2.1 Setup

The static TT is conducted using a universal testing machine (Shimadzu AG-X), as illustrated in Figure 28.

Figure 28: Shimadzu AG-X tensile test setup

A 5kN load cell (specified in 11.2) is connected to the upper jaw. The support distance is set accordingly to the specimen geometry. A HD camera (specified in 11.3) is placed in front of the testing chamber, angled orthogonally towards the centre of the flat specimen surface. The specimens are placed inside the self-clamping jaws with the aid of slim polycarbonate plate plates for centring measures.

6.2.2 Measurement and evaluation method

Standard testing velocities are 1mm/s and 0,1mm/s. Regarding the geometry and the testing velocity it is possible to achieve different starting strain rates.

Force is measured directly via the loading cell. Strain is calculated over a Digital Image Correlation (DIC) system to receive exact surface strain information of the parallel area. DIC measurements are conducted with the software Mercury RT (latest version) by Sobriety. For static testing, the HD Camera IDS UI-3180CP Rev. 2.1 is used, which has a maximum resolution of 2592x2048 (5.31 MP, 73 fps). In dynamic measurements the high-speed camera Photron FASTCAM NOVA with a maximum resolution of 1024x1024 (1 MP, 9000fps) is used. Resolution of the cameras is adjusted to view the relevant lengths of the specimen over the entirety of the testing period, whilst using the highest possible framerate.

By using a camera, the operator is responsible to position them in designated rigid stands for the respective measurement, in order to ensure a valid calibration of the coordinate system with reprojection errors lower than 0.5. Premade DIC patterns are used and must be checked and verified regularly.

All DIC measured specimens are sprayed with a black and white statistical speckle pattern, depicted in Figure 29. Alternatively, a point pattern can be applied.

Two-dimensional DIC markers are set within the "full field" and measure at a fixed distance of 2/4mm, depending on the specimen geometry, as seen in Figure 29.
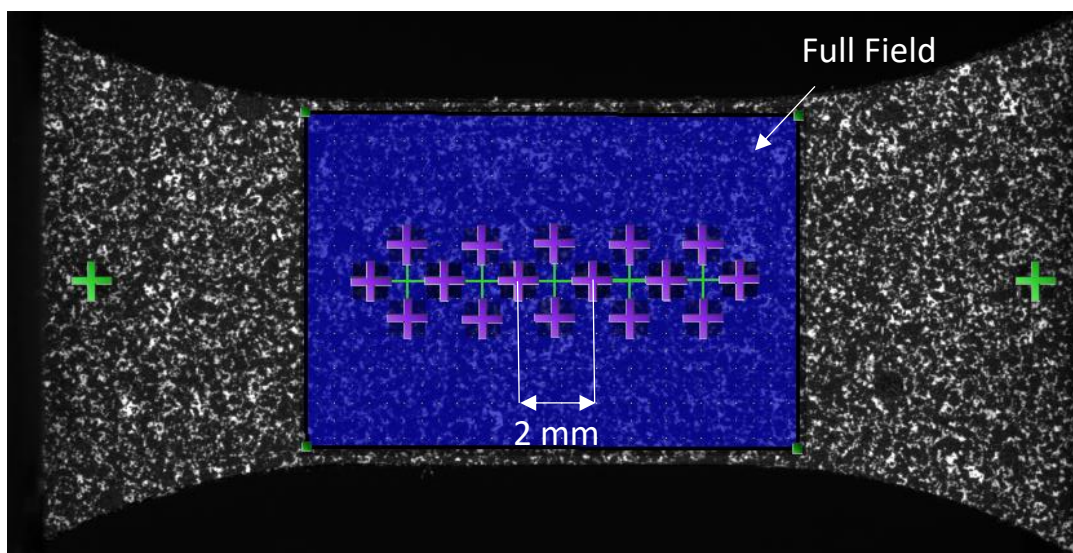

Figure 29: Digital image correlation (DIC) strain measurement on a standard Type3 specimen

Between each marker the physical strain is calculated based on the differential equation shown in (9). The max. strain occurring will be further used in calculation.

$$\varepsilon_t(t) = \sum_{lo}^{li} dl/l = \ln\left(\frac{l_i}{l_0}\right) \qquad (9)$$

ε_t … True strain
l_0 … Starting marker distance
l_i … Marker distance at time i

Depending on the desired material model arising from this test, the physical stress is calculated on the area which narrows during dilatation following either a Poisson's ratio of 0.5 or with the measured

Poisson's ratio using the orthogonal placed markers. Either way the true strain can be defined as shown in (10).

$$\sigma_t(t) = \frac{F_i}{A_i} \tag{10}$$

σ_t … True stress
F_i … Force measured at time i
A_i … Area at time i, calculated based on v=0.5 or alternatively v=measured

To confirm the received data, the strain is double checked (outer markers – average strain) with the displacement information of the crosshead position.

Relevant measurements regard the parallel area within the specimen. A typical result is displayed on Figure 30.
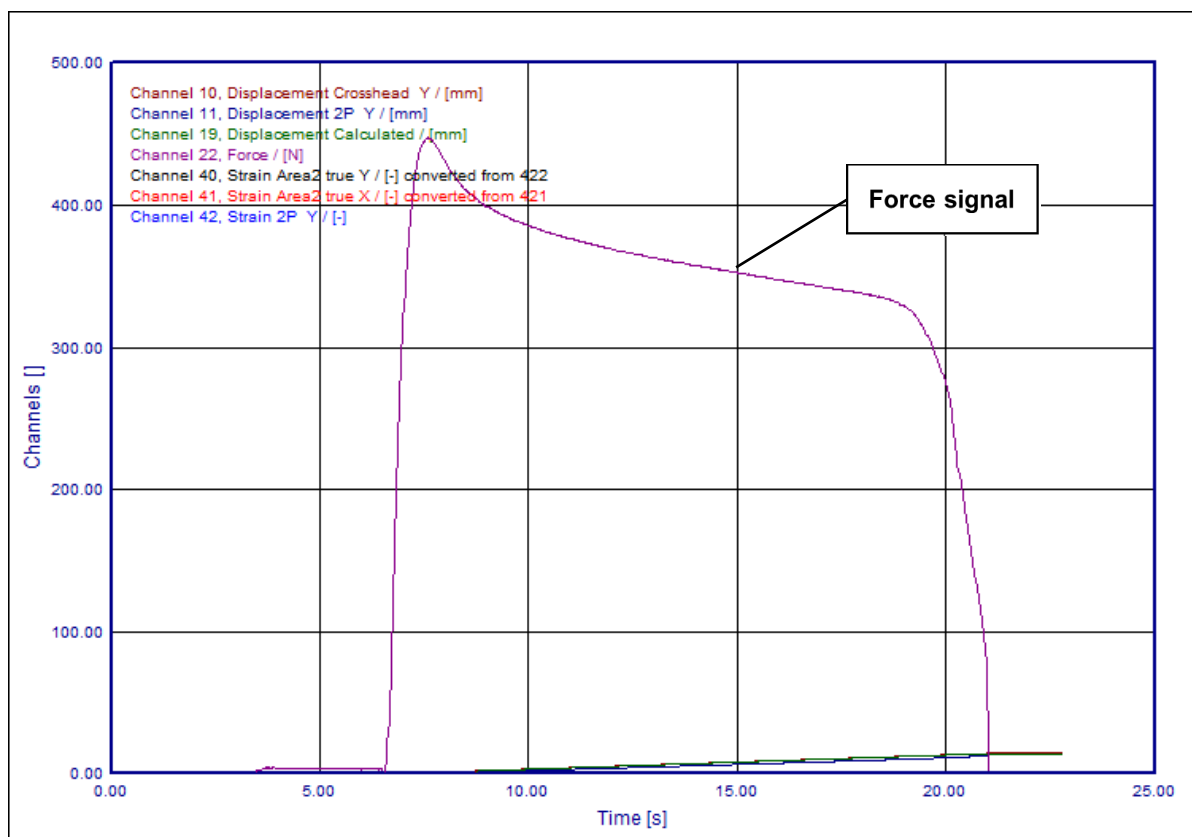
Figure 30: Example result for force of a static TT

Evaluation in ISO 527 is analogue.

6.2.3 Cyclic testing

Analogue to the static cyclic 3PB, for more information look at 5.2.3. Strain measurement via DIC, as described in the static TT 6.2.2.

6.3 Dynamic testing

6.3.1 Setup

Dynamic tensile tests are conducted on a 4a IMPETUS® pendulum. This test utilizes a clamping set which is not attached to the rest of the testing machine and is depicted in Figure 31.

Figure 31: Testing specimen with clamping set in placing template

The operator is required to use the placing template for exact placement and a torque wrench to evenly distribute a defined contact pressure.

A support bearing, which is screwed down on the machine, is used to place the specimen with the clamping set in the testing machine. A scalable (20%, 100%) 20kN load cell (specified in 11.2) is connected to the rear end of the support bearing, which further connects the rear pin of the clamping set to the support bearing. A high-speed camera (specified in 11.3) is placed in on the side of the test rig, angled orthogonally towards the centre of the flat specimen surface. The setup is depicted on Figure 32. After clamping the specimen, it is placed on the support bearing as pictured in Figure 33. A swing hammer mass of 3510g is used.
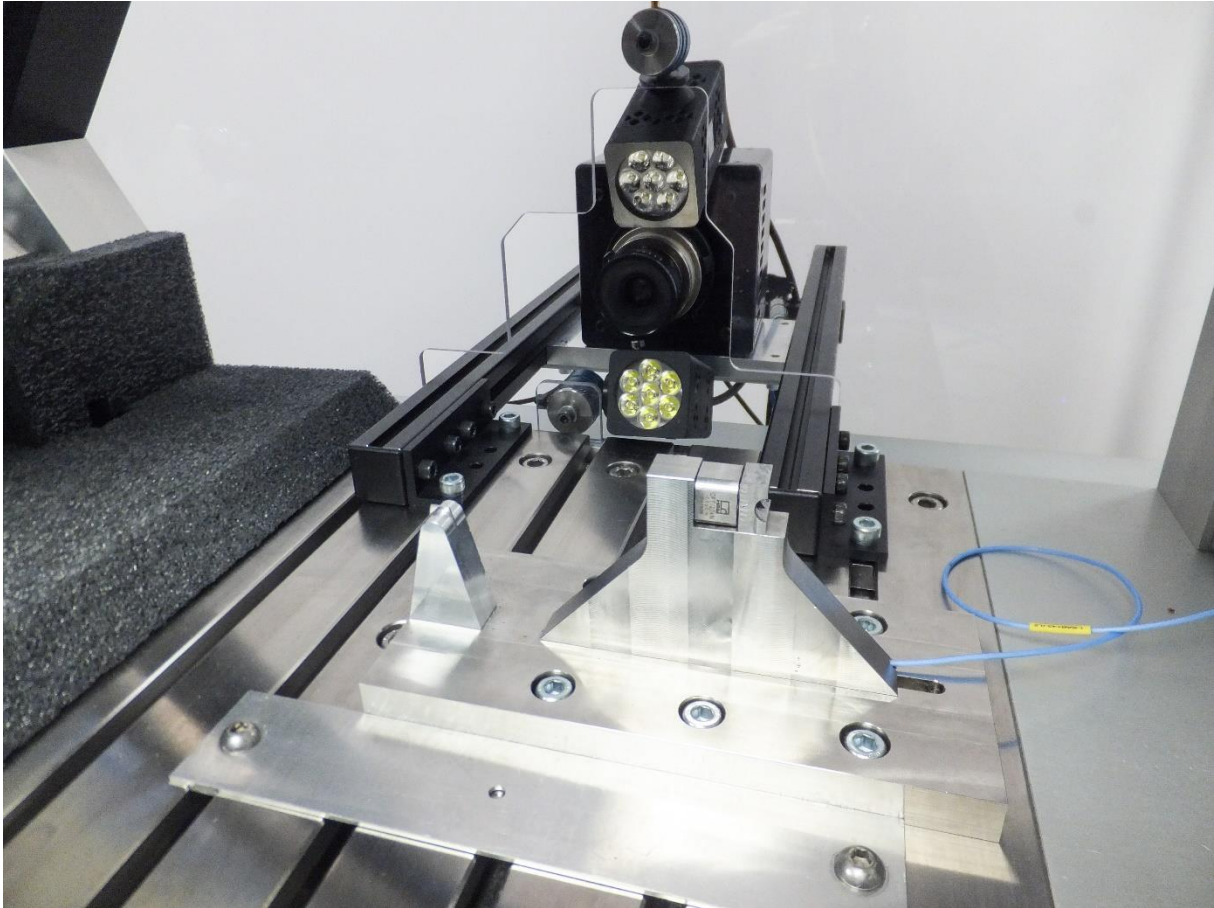
Figure 32: Dynamic tensile test setup

Figure 33: Specimen placed on the support bearing for the dynamic tensile test

6.3.2 Measurement and evaluation method

The standard test velocity is 2.5m/s. The force is measured directly via the loading cell. The strain is measured optical via DIC, analogue to the static TT, described in 6.2.2. A typical result is displayed in Figure 34. Take in regard that the scatter induced in the test curves is due to dynamic swinging phenomena. Relevant measurements regard the parallel area within the specimen.
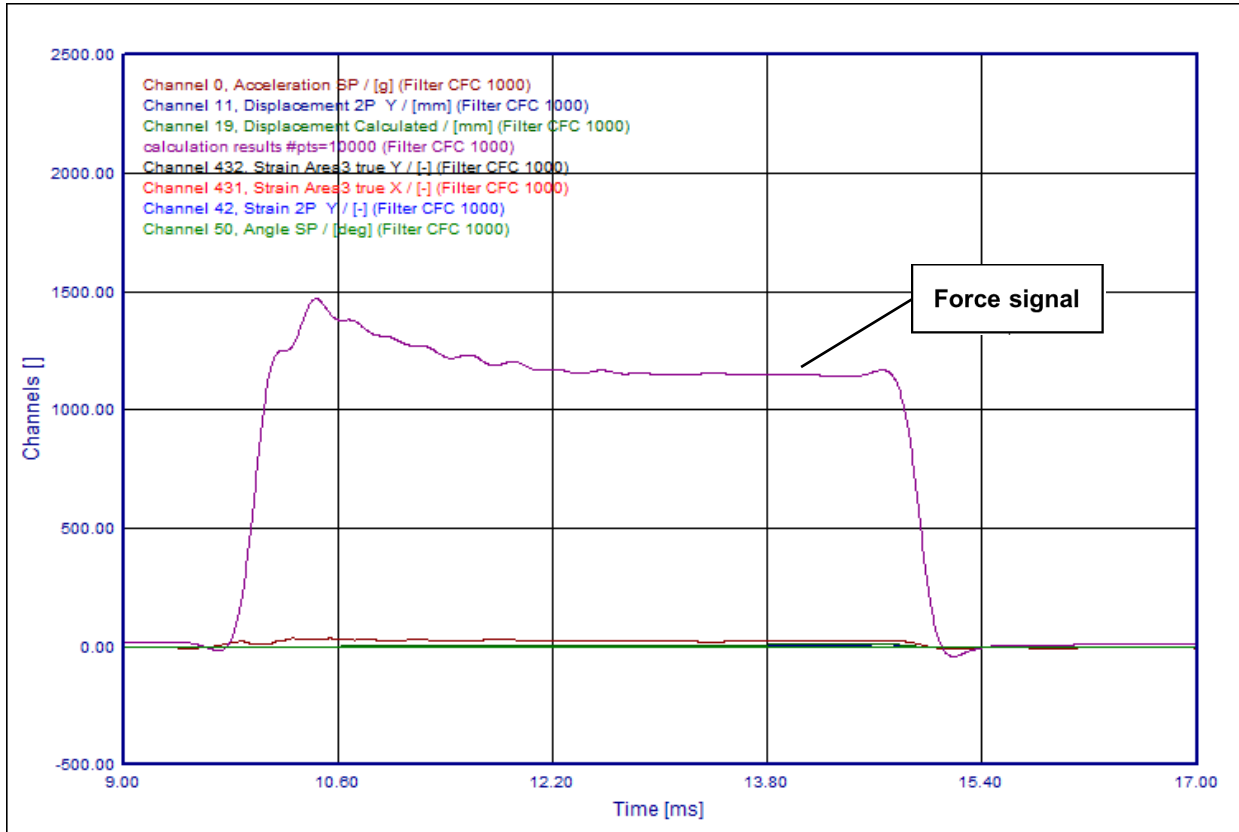
Figure 34: Example result for force of a dynamic TT

7 Puncture test (PT)

7.1 Specimen geometry

Following specimens are used for the puncture tests:

- IMPETUS®-PT-STAT-V1, 80x80x2 (static standard, Figure 35)
- IMPETUS®-PT-DYN-V1, 120x80x2 (dynamic standard, Figure 36)
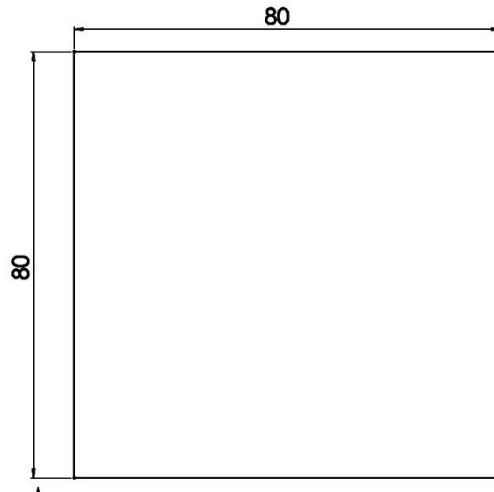
Figure 35: Standard specimen IMPETUS®-PT-STAT-V1 for static puncture test
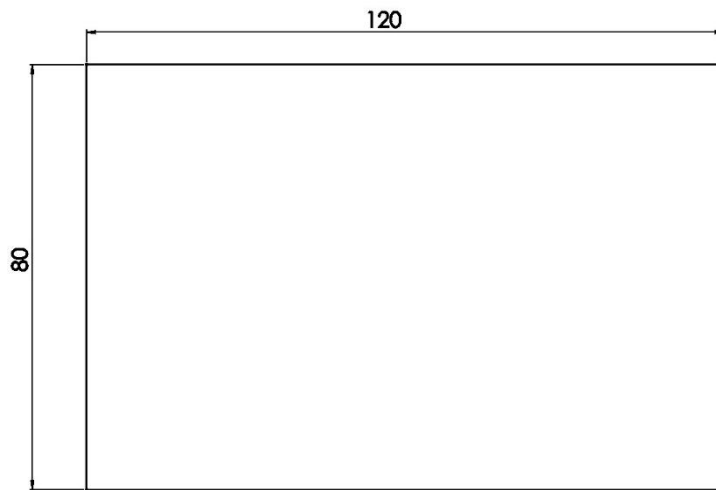
Figure 36: Standard specimen IMPETUS®-PT-DYN-V1 for dynamic puncture test

The 120x80x2 specimen is directly cut off the 4a mold, the 80x80x2 specimen is sawed out of the centre of the 120x80x2 plate.

7.2   Static testing

7.2.1   Setup

Static puncture tests are conducted on a universal testing machine (Shimadzu AG-X). Clamping plates with a support diameter of 42mm (radius of 1mm) and a free diameter of 44mm are used to hold the specimen in place. The specimen is clamped and centred using 4 screws. A 5kN loading cell (specified in 11.2) is connected over a pedestal to the clamping plate. For intrusion, a hemispherical impactor with a radius of 10mm (5mm for ductile materials) is used. The setup is shown in Figure 37.

Figure 37: Static puncture test setup

7.2.2   Measurement and evaluation method

Force is directly measured via the loading cell, displacement via the crosshead position. Standard test velocity is 1mm/s. A typical result is depicted in Figure 38.

In the puncture test there are three distinct failing mechanism observed, which result in specific curves and breaking patterns, shown in Figure 39.

Relevant specimen measurements are depicted on Figure 40.

Furthermore, the penetration energy is calculated using the equation (11) and also taken into consideration.

$$E = \int_0^{f_c} F \, df \qquad (11)$$

E … Penetration energy
f_c … Deformation at failing point

Evaluation is based on ISO 6603.
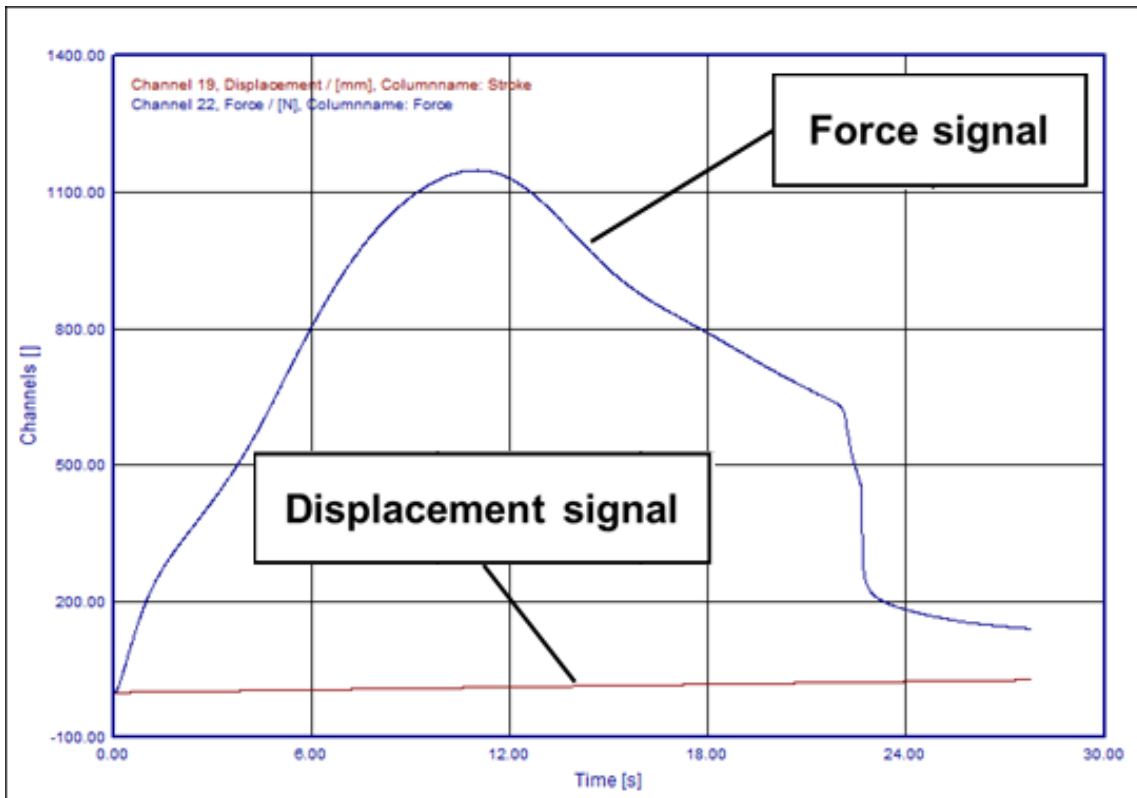
Figure 38: Example result for force and displacement of a static PT
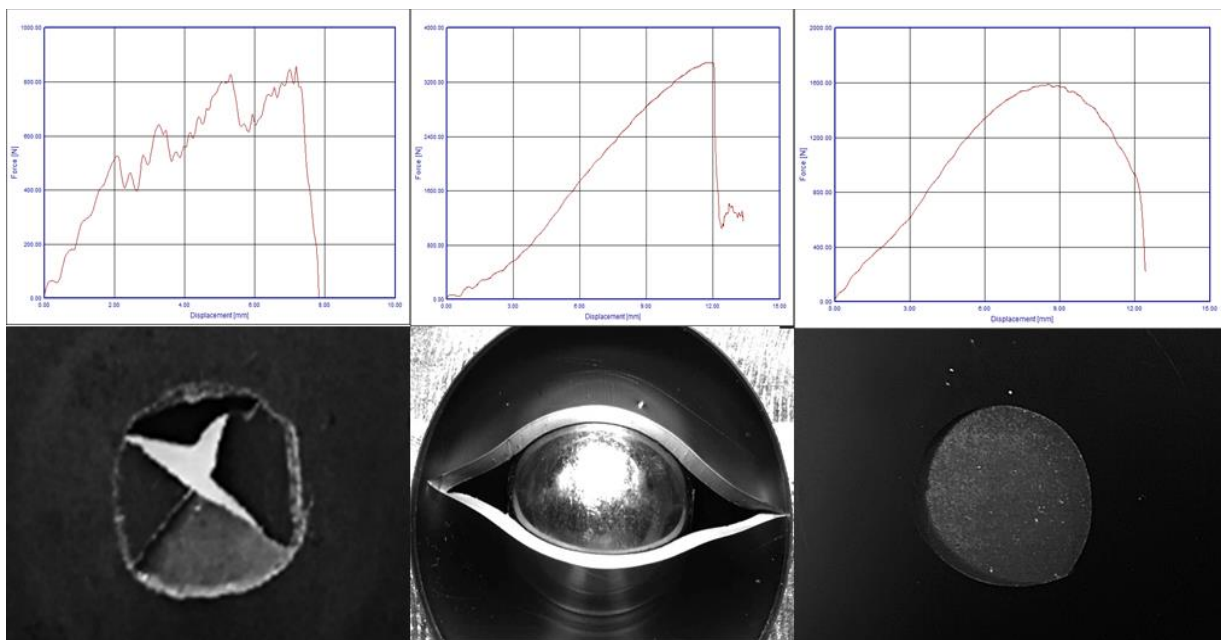
Figure 39: Characteristic failing mechanisms PT, depending on load speed, temperature and material, from left to right: no yielding, brittle cracking; yielding and cracking; yielding and deep drawing
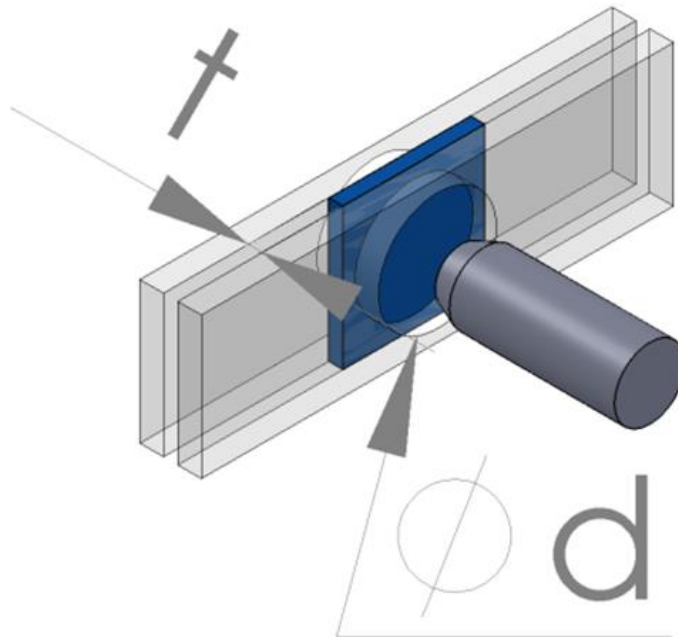
Figure 40: Relevant specimen measurements for testing

7.3 Dynamic testing

7.3.1 Setup

Dynamic puncture tests are conducted on a 4a IMPETUS® testing pendulum. The hammer weighs 3218.4g and is equipped with an 400g (g for gravitational constant) acceleration sensor (specified in 11.2). The specimen is clamped within two holding plates, having a free diameter of 50mm and a support diameter of 42mm (radius=1mm). The holding plates are placed in the counter bearing and are held in place by pressure exerted from pulling a spring powered lever. The counter bearing is equipped with an 25g acceleration sensor (specified in 11.2). For intrusion, a hemispherical impactor with a radius of 10mm (5mm for ductile materials) is used. The setup is shown in Figure 41.
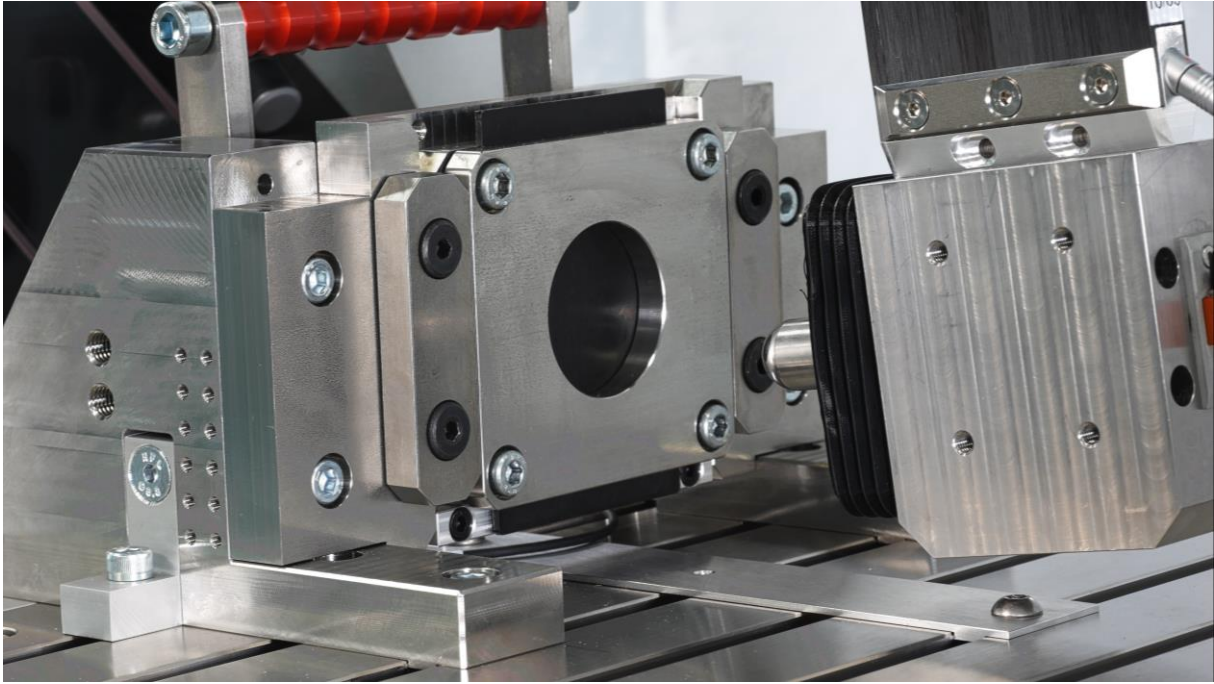
Figure 41: Dynamic puncture test setup

7.3.2 Measurement and evaluation method

The standard test velocity is 3m/s. Measurement and calculation analogue to dynamic 3PB, look at 3.3.2 for more information. A typical result is displayed on Figure 42. Take in regard that the scatter induced in the test curves is due to dynamic swinging phenomena.
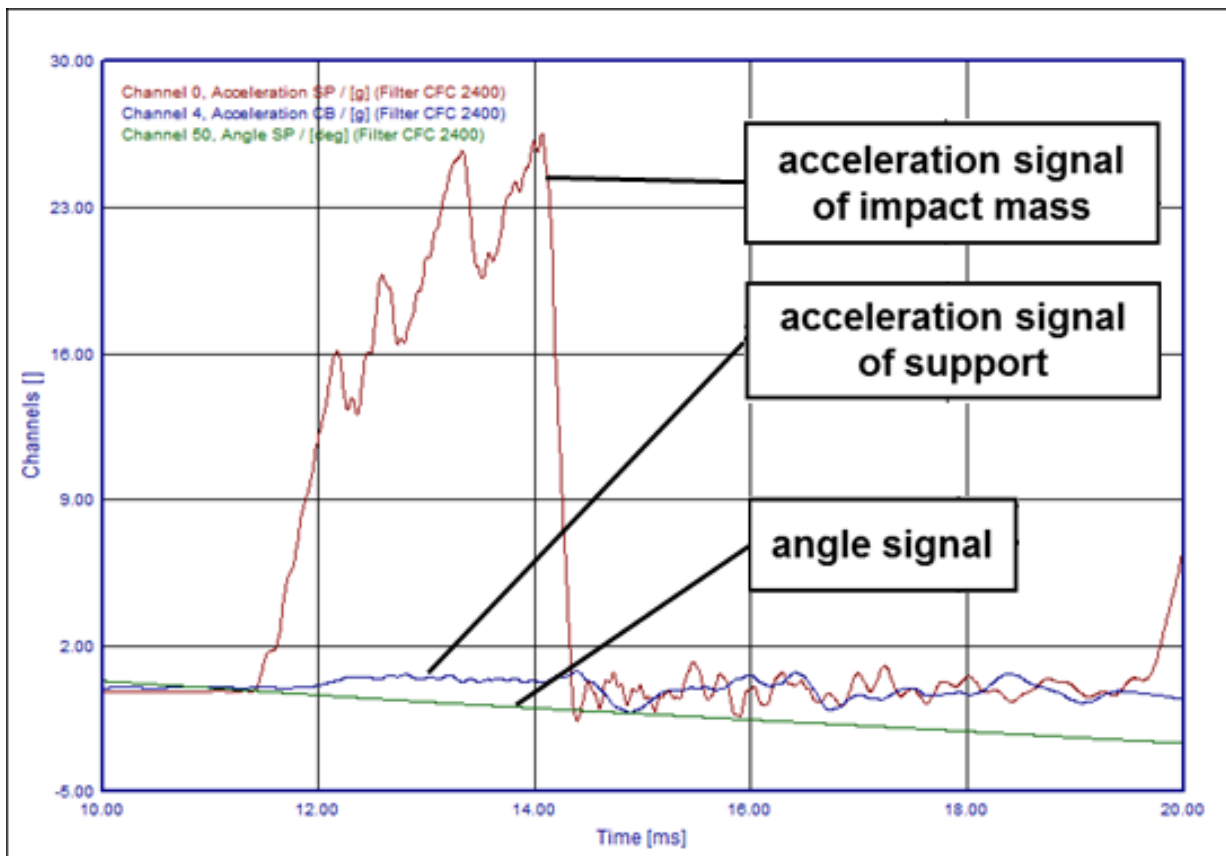

Figure 42: Example result for acceleration and angle of a dynamic PT

8   Shear test (ST)

8.1   Specimen geometry

Following specimens are used for the shear tests:

- IMPETUS®-SH-V1 ("Butterfly", standard, static only, Figure 43)
- IMPETUS®-SH-V2 (ASTM-B831 modified, optional, static and dynamic, Figure 44)
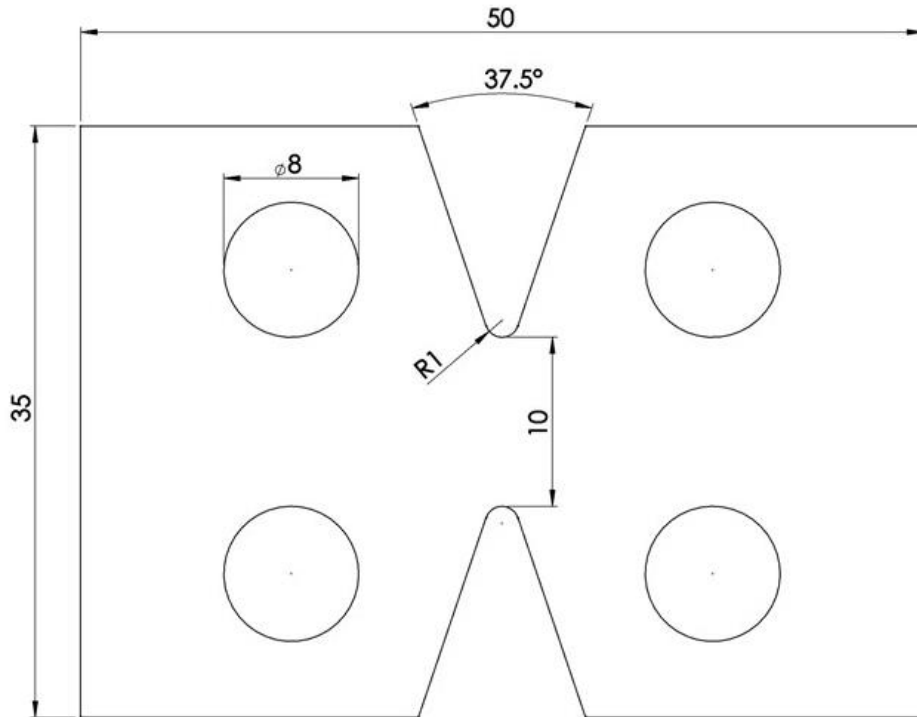- IMPETUS®-SH-V3 (ASTM-B831 modified, optional, static and dynamic, Figure 45)

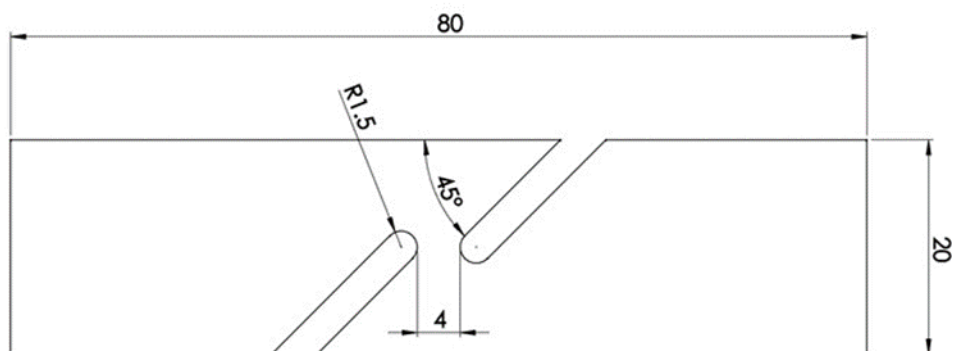*Figure 43: IMPETUS®-SH-V1, standard specimen for static shear test*

Figure 44: IMPETUS®-SH-V2, optional specimen for shear test
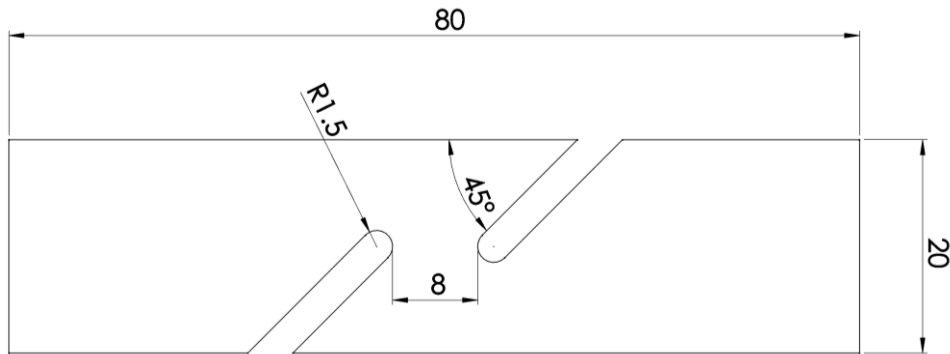
Figure 45: IMPETUS®-SH-V3, optional specimen for shear test

8.2   Static testing

8.2.1   *Setup*

Static shear tests are conducted on a universal testing machine (Shimadzu AG-X). For the ASTM-B831-modified specimen (V2&V3) the setup used is equivalent to the static TT (6.2.1). Butterfly specimens are tested by using two clamping plates on each side, which are screwed together through the boreholes on the specimen. Thus, introducing the force over the surface area and avoiding pulling directly on the boreholes, reducing the risk of failure in unwanted areas. The clamping plates are clamped themselves within the jaws of the machine. Since the jaws used for holding the clamping plates are dimensioned for testing metals, they are significantly bigger than the ones used for the static TT (6.2.1). This requires the usage of a 50kN load cell (specified in 11.2). The butterfly setup is shown in Figure 46.

Figure 46: Test setup for butterly specimen, static tensile test 50kN

In both setups a HD camera (11.3) is placed in front of the test specimen, angled orthogonally towards the centre of the flat specimen surface.

8.2.2 *Measurement and evaluation method*

Standard testing velocity for the static shear test is 0.1mm/s. Relevant measurements of the test specimen for static shear test is illustrated on Figure 47. The force is directly measured via the loading cell. The shear strain is obtained from the DIC system, illustrated on Figure 48.

Force is measured directly via the load cell. Shear strain is calculated over a digital image correlation system to receive exact surface strain information. The shear strains are measured over a two-dimensional full-field DIC pattern on the surface of the sample. In addition, the local displacement of the sample is recorded using 2 markers near the chuck, depending on the specimen geometry, as seen in Figure 49.

Test-Setup	v_0 [m/s]	L [mm]	B [mm]	B_i [mm]	t [mm]	R [mm]
ST_stat	0.0001	10	35	10	2	1

Table 8: Testing parameters static ST - butterfly specimen
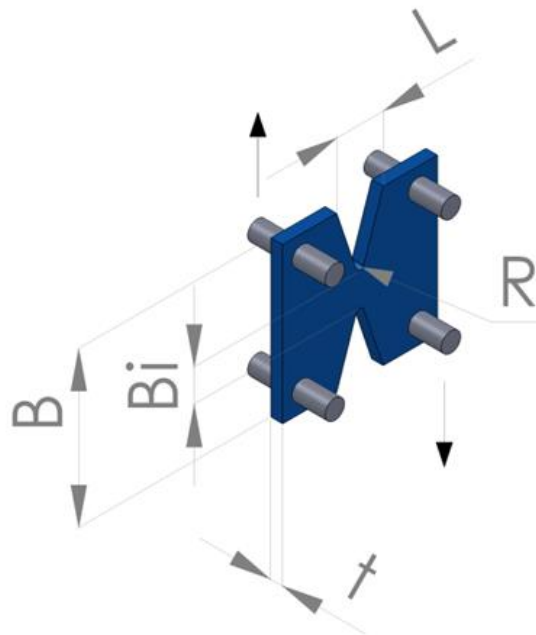

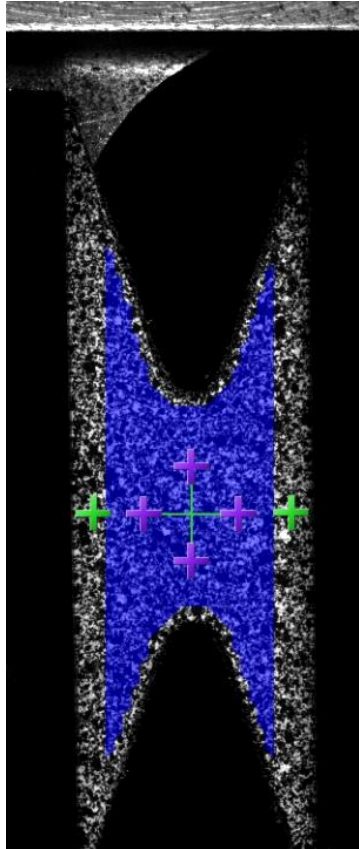*Figure 47: Relevant specimen measurements for the ST - butterfly*
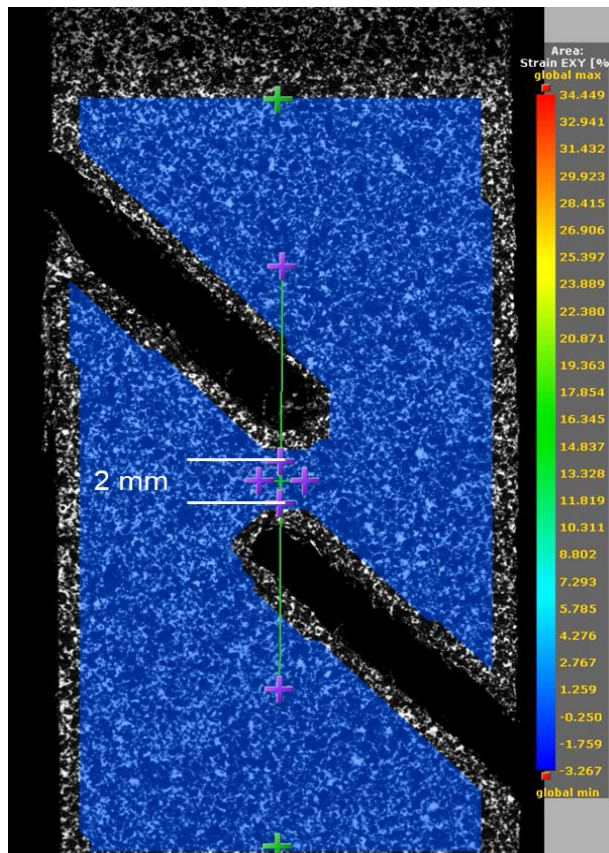
Figure 48: DIC measurement for ST

Figure 49: DIC measurement for ST with specimen V2

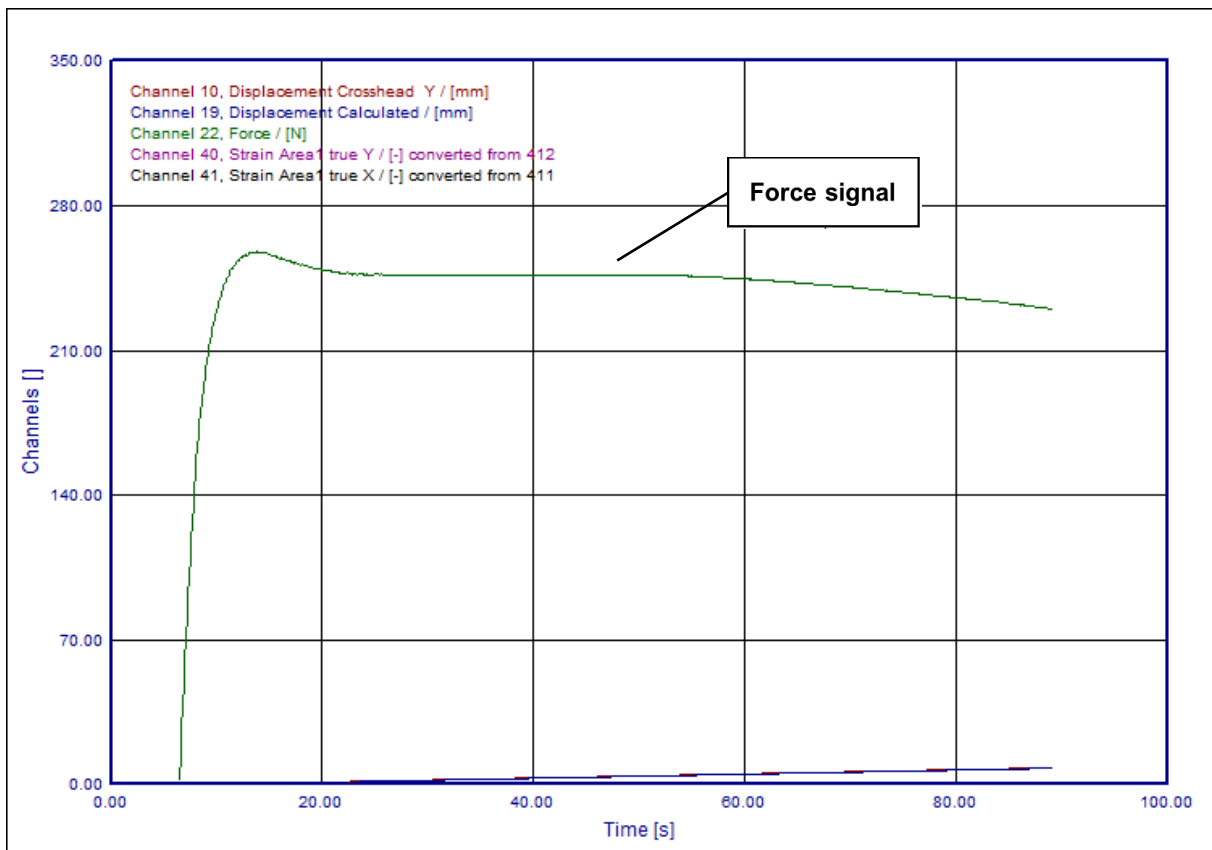A typical result of a static shear test is displayed on Figure 50

Figure 50: Example result of a static ST

8.3 Dynamic testing

8.3.1 *Setup*

The dynamic shear tests are conducted on a 4a IMPETUS® pendulum. With the 4a IMPETUS® it is possible to test the ASTM-B831-modified specimen (V2&V3) analogue to the dynamic TT. For further information on the structure of the dynamic tensile test, look at point 6.3.

8.3.2 *Measurement and evaluation method*

The standard test velocity is 2.5m/s. The force is measured directly via the loading cell. The strain is measured optical via DIC, analogue to the static ST, described in 8.2.2. A typical result is displayed in Figure 51. Basically, the measuring is analogue to the dynamic tensile test described in 6.3.
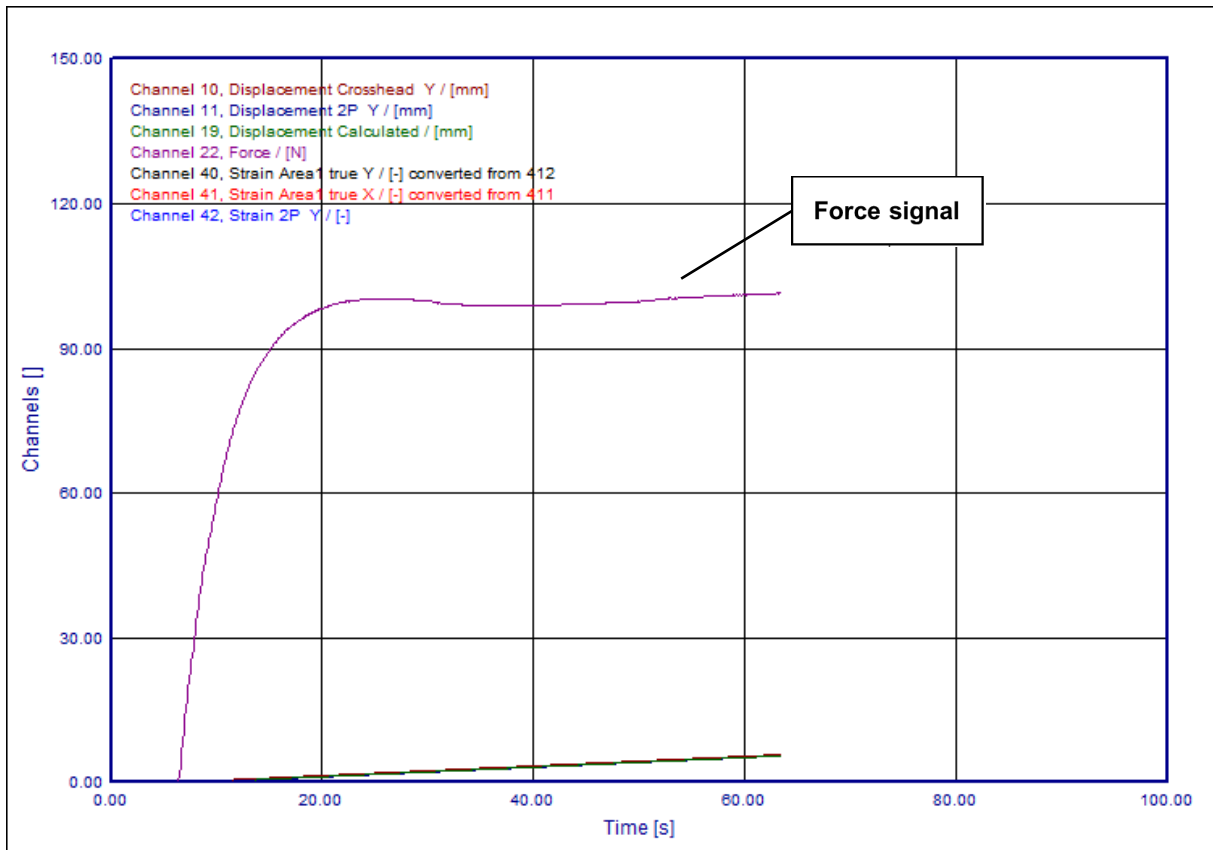
Figure 51: Example result of a dynamic ST

9   Compression test (CT)

9.1   Specimen geometry

Following specimens are used for the compression tests:

- IMPETUS®-CT-Cube 3x3x2 (optional) (Figure 52)
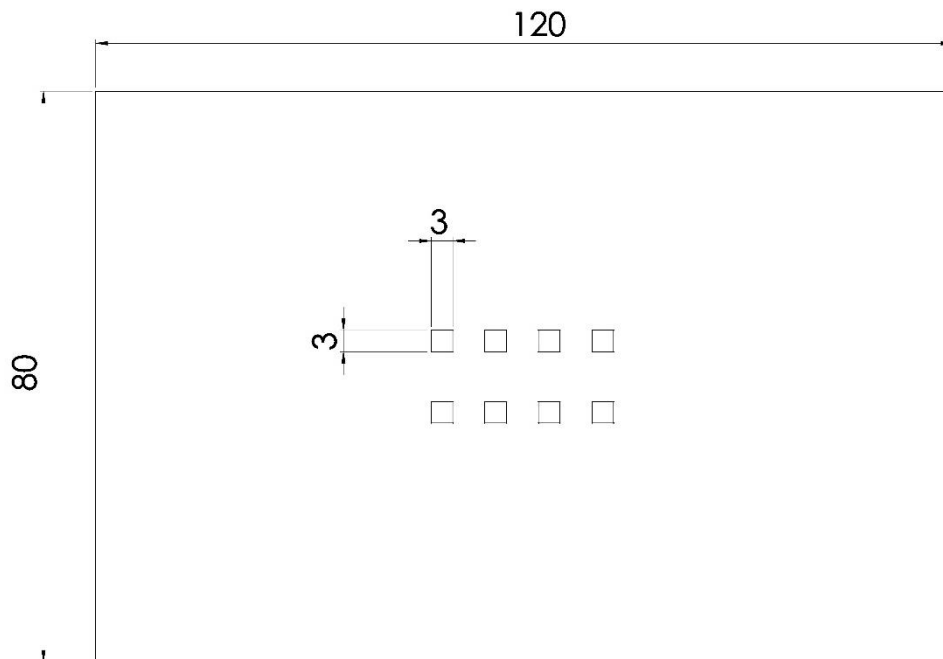- IMPETUS®-CT-Celanese 50x10x2 (standard)(Figure 53)

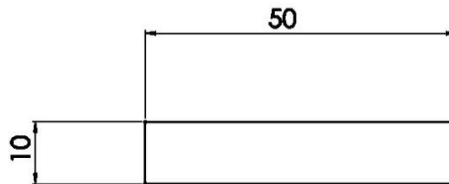*Figure 52: Compression test specimen IMPETUS®-CT-Cube, milling pattern*

Figure 53: Compression test specimen IMPETUS®-CT-Celanese 50x10x2

9.2   Static testing

9.2.1   *Setup*

The static compression test is conducted on a universal testing machine (Shimadzu AG-X). The cube specimens are placed between two flat surfaces, the upper one being connected to a 5kN load cell (specified in 11.2). A HD camera (11.3) is placed in front of the testing specimen, angled orthogonally towards the centre of the flat specimen surface. The setup is depicted on Figure 54.

The Celanese-CT specimens are put into four metal bodies forming a cone, which are then put into a negative shaped conical form which applies pressure on the specimen by the weight of the bodies. The applied clamping force holds the sample and assembly in place, shown on Figure 55. The whole setup is then put into a metal guide for measuring, as depicted in Figure 56.
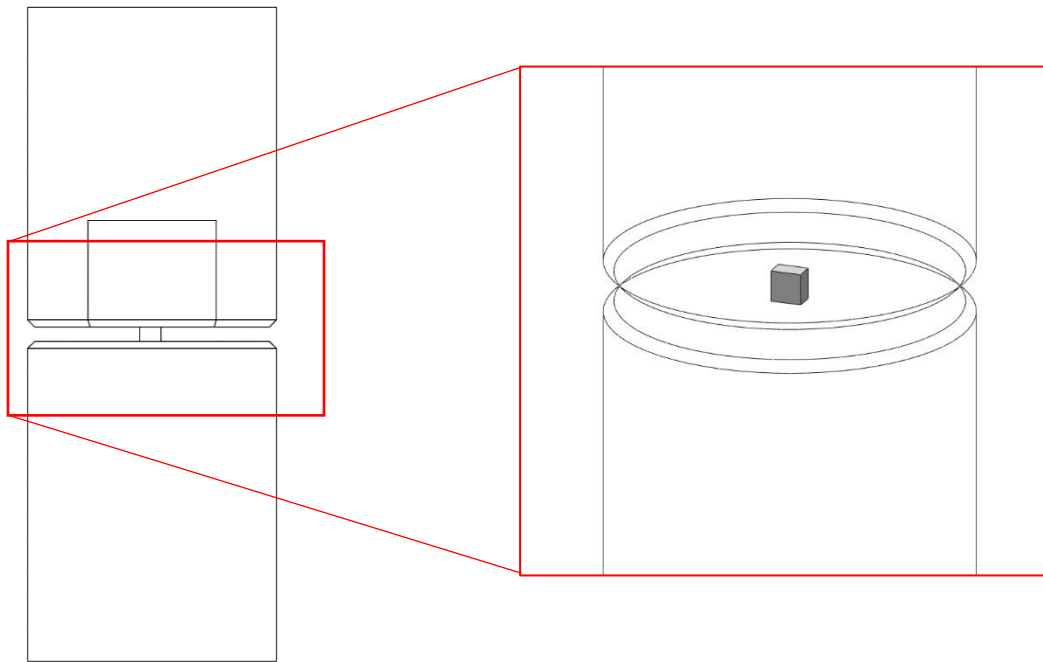
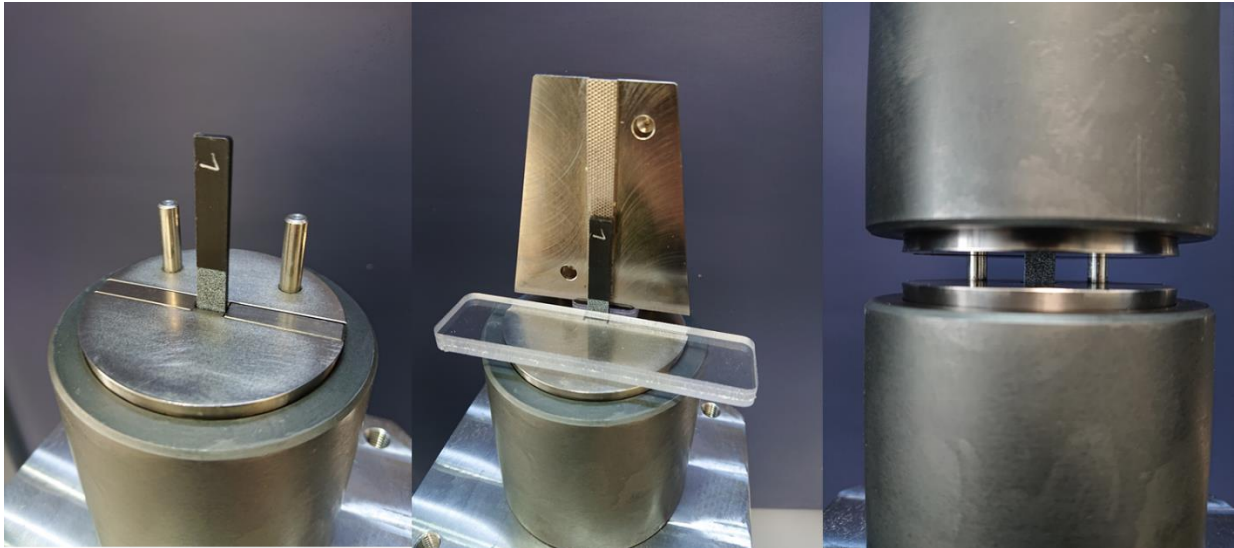*Figure 54: Static compression test setup, cube specimen*

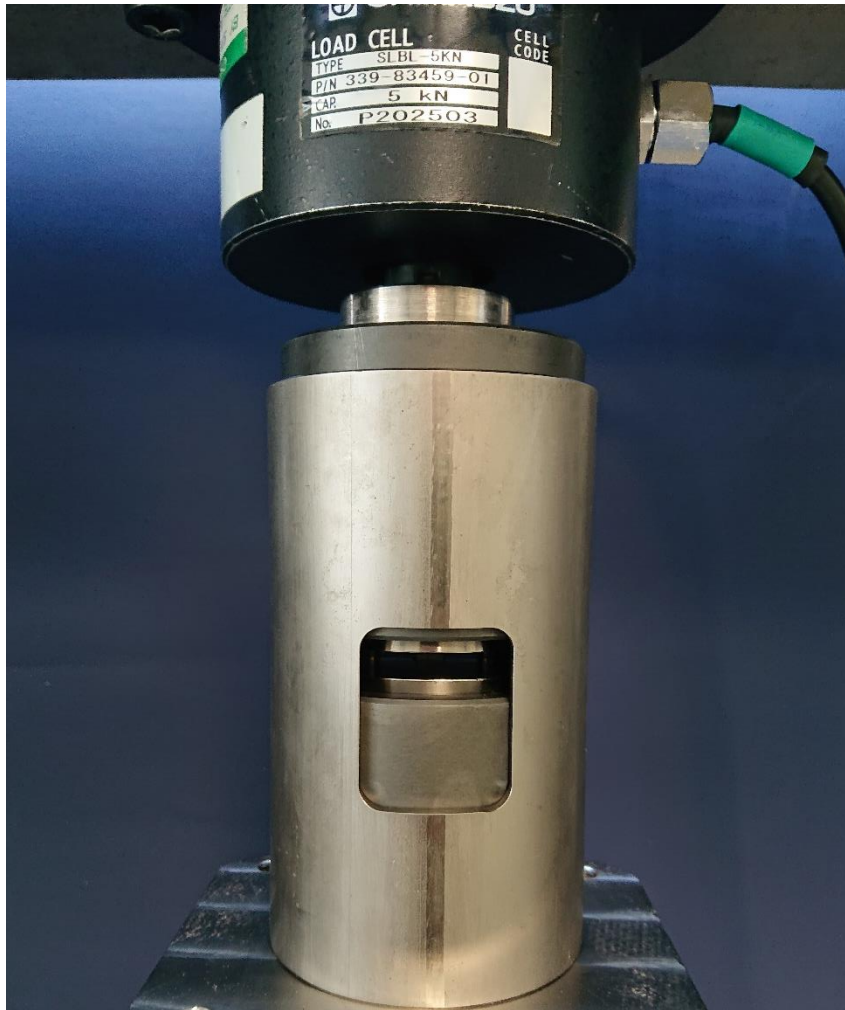*Figure 55: Clamping the Celanese specimen*

Figure 56: Final setup for compression testing Celanese-CT

9.2.2 Measurement and evaluation method

The force is directly measured via the load cell. Standard testing velocities and correlating starting strain rates $\dot{\varepsilon}^*$ are shown in Table 9 and Table 10, relevant specimen measurements are depicted on Figure 57. The strain is calculated using optical DIC, as described for the static TT (6.2.2) and depicted in Figure 58.

Test-Setup	v_0 [m/s]	L [mm]	b [mm]	t [mm]	$\dot{\varepsilon}^*$ [1/s]
CT_stat (cube)	0.0001	3	2	3	0.0333

Table 9: Testing parameters static CT - Cube

Test-Setup	v_0 [m/s]	L [mm]	b [mm]	t [mm]	$\dot{\varepsilon}^*$ [1/s]
CT_stat (Celanese)	0.0001	10	2	6	0.0167

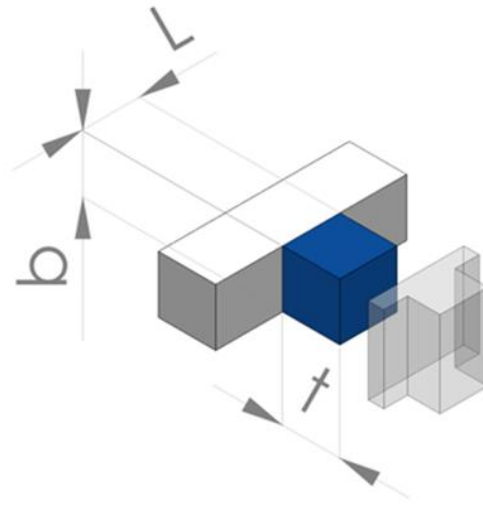*Table 10: Testing parameters static CT - Celanese*

Figure 57: Relevant specimen measurements for the compression test
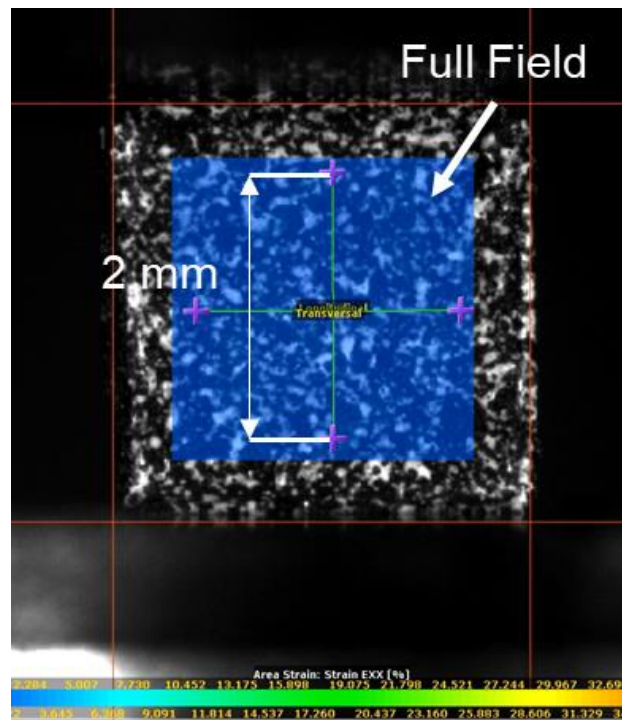

Figure 58: Digital image correlation (DIC) strain measurement CT

10 Validation – Component test (COT)

The primary goal of material testing is to extract material data for the generation of reliable material cards, to accurately simulate real loading cases. To ensure the integrity of this process, the last step is validating the material cards by simulating tests on frequently occurring geometries used in plastic designs and then comparing the results by testing these geometries physically. The tests are described following.

10.1 XX-ribs (COT based on 3PB)

The XX-rib component is sawed of the multi specimen plate (Figure 6). Its distinct geometry is further highlighted in Figure 59.
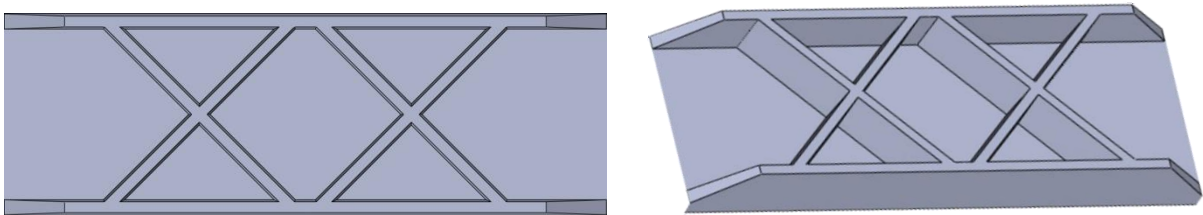

Figure 59: XX-rib component

The test is conducted on a 4a IMPETUS® pendulum, utilizing a 5g (g for gravitational constant) acceleration sensor (specified in 11.2) on the counter bearing, a 400g acceleration sensor (specified in 11.2) on the pendulum hammer, a swing hammer mass of 1580g and a support and fin radius of 2mm. The counter bearing is specially designed to hold the specimen in place. The setup is pictured on Figure 60.

Figure 60: XX-Rib component test setup

The standard testing velocity is 3m/s, the processing and calculation methods for the signals are equal to the dynamic 3PB (5.3) A typical result is displayed on Figure 61.
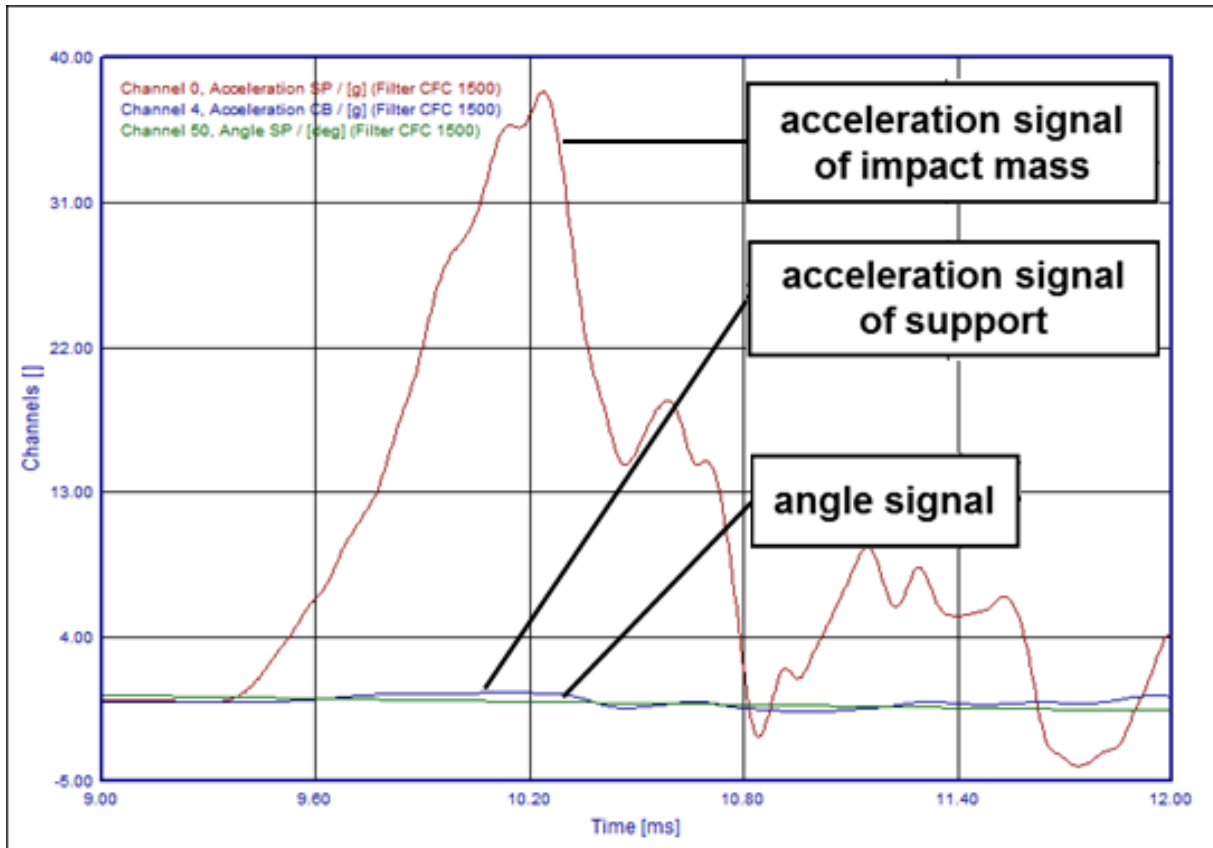

Figure 61: Example result for acceleration and angle of a XX-Rib component test

Take in regard that the scatter induced in the test curves is due to dynamic swinging phenomena.

11 Appendix

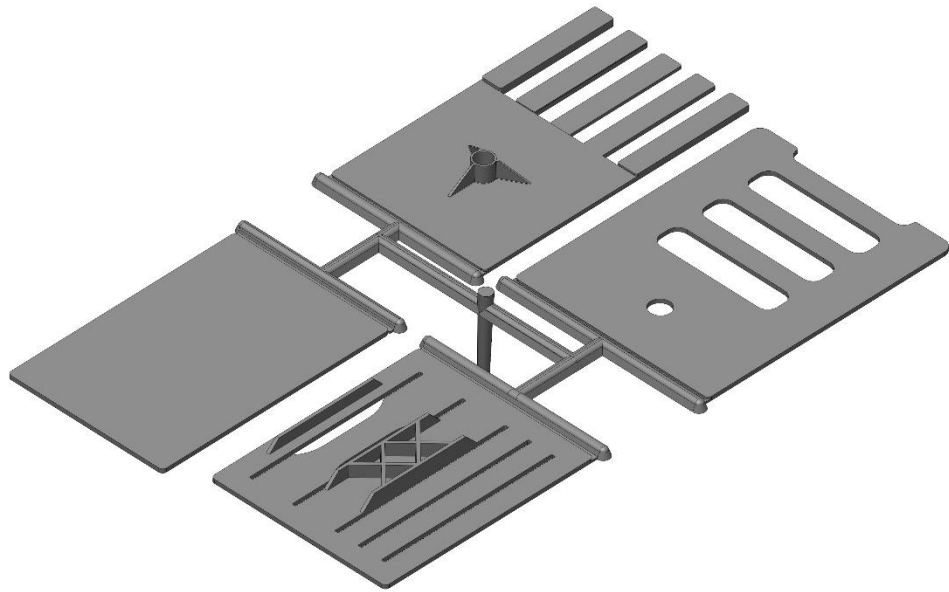## 11.1 Injection mold for research available on request

Figure 62: Research injection mold

The research injection mold is available on request from the customer. Non-standard specimens can be obtained from the melt- & weld line plate (Figure 63) and the Dome & finger (Figure 64) plate.
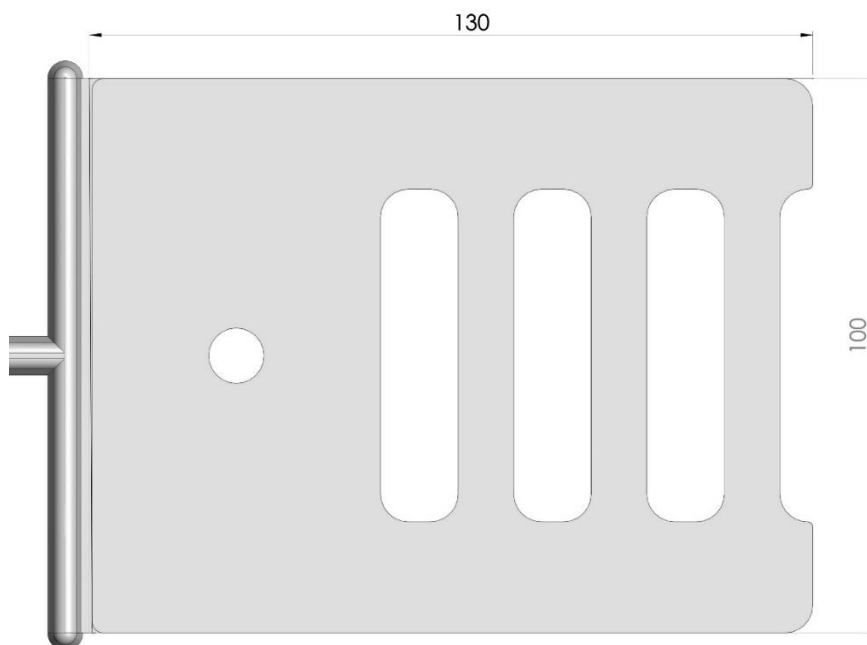

Figure 63: Melt- & weld line plate
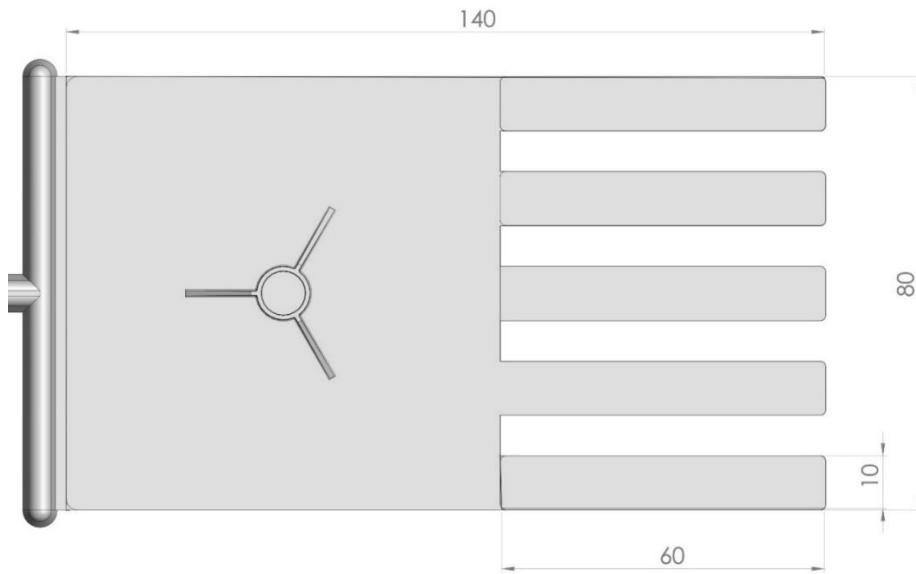
Figure 64: Dome & finger plate

11.2 Dome (COT based on PT)

The Dome component is sawed off the Dome & finger plate (Figure 64). Its distinct geometry is further depicted in Figure 65.

Figure 65: Dome component

The test is conducted on a 4a IMPETUS® pendulum, using the same setup and measurement methods described in section 7.3 for the dynamic puncture test. The distinct feature on the plate is facing away from the pendulums swinging direction. A typical result is displayed in Figure 66.

Figure 66: Example result for acceleration and angle of Dome component test
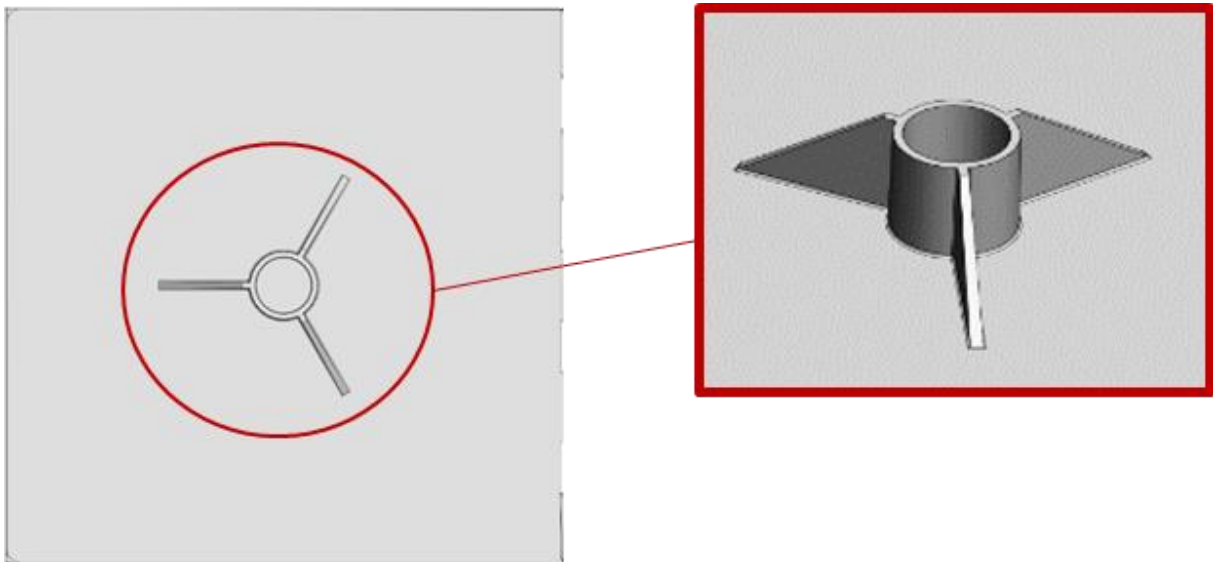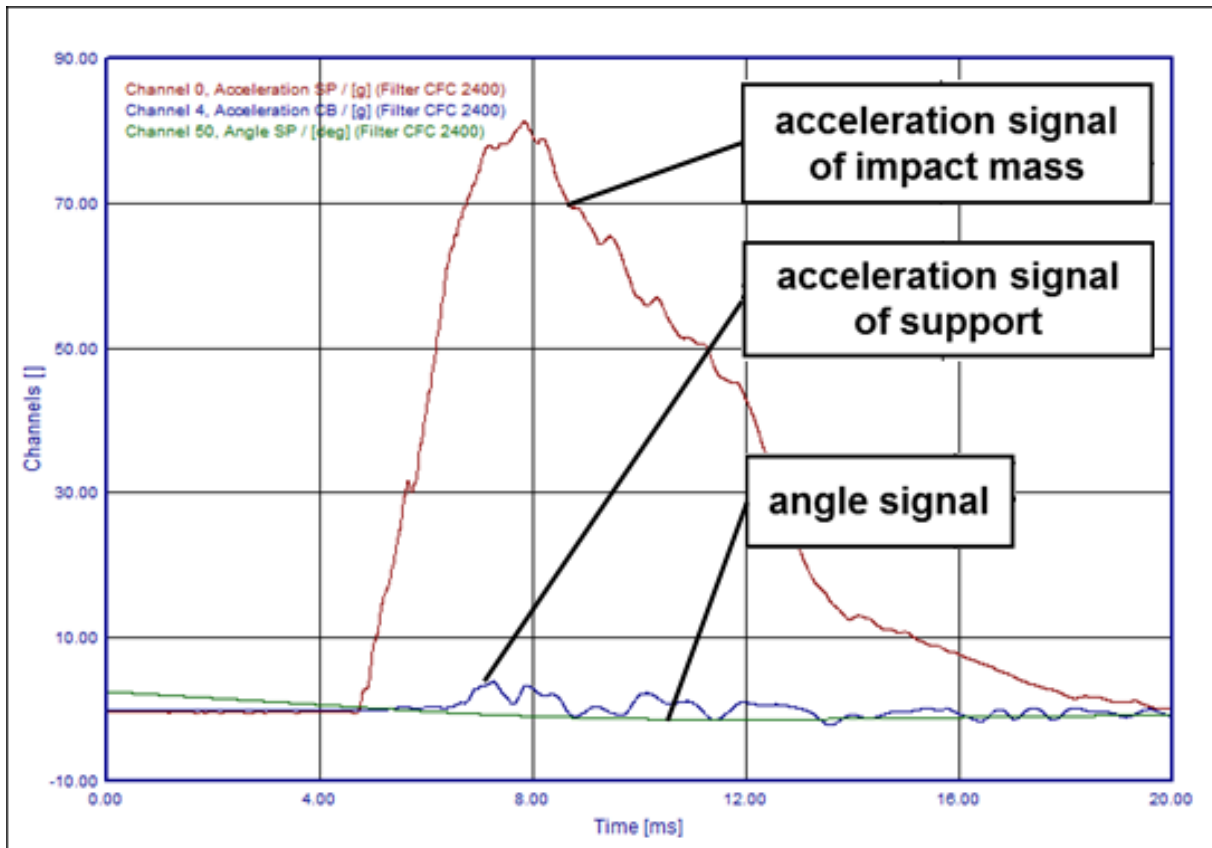
Take in regard that the scatter induced in the test curves is due to dynamic swinging phenomena.

11.3 Tolerances

11.3.1 Specimen geometries

Specimens are measured in thickness with a digital dial indicator (specified in 11.4), other dimensions are taken with a digital calliper (specified in 11.4).

Evaluation relevant measurements are documented individually and tolerated within the range of ±0.05mm, or elsewise discarded. Other measurements, such as total length is averaged over the first five specimen for each setup and conform to a tolerance of ±1mm.

11.3.2 Velocities

Static tests are conducted with a maximum deviation in velocity of ±1%, dynamic tests ±10%. Either way the exact velocity is documented with a maximum precision of the respective sensor.

11.4 Sensor information

Measuring equipment is checked and calibrated regularly. Table 11 illustrates calibration intervals, measurement range, resolution and tolerances for sensors and equipment.

Type	Serial - Nr.	Range	Resolution	Tolerance	Interval [y]
Calliper	Sylvac S_CalPro IP6736136	0 - 150mm	0.01 mm	± 0.01 mm	1
Calliper	Sylvac S_CalONE003888	0 - 150mm	0.01 mm	± 0.01 mm	1
Digital dial indicator	Sylvac S_Dial Work BASIC13469420	0 - 12.5 mm	0.001 mm	± 0.004 mm	1
Digital dial indicator	Sylvac S-Dial Work13269157	0-25 mm	0.01 mm	± 0.01 mm	1
Scale	sartorius CPA225D-0CE23011313	0 - 220 g	0.0001 g	± 0.0002	3
Furnace	Memmert UF110plusB415.0375	20 - 250 °C	0.1 °C	± 1 °C	3
Furnace	Memmert UF30plusB119.0960	20 - 250 °C	0.1 °C	± 1 °C	3
Climatic chamber	Memmert HPP 110W413.0062	5 - 70 °C10 - 90 % rh	0.1 °C0.1 % rh	± 1°C± 2%	3
Cooling chamber	ARCTIKO/ULUF6021.18 1081016	-20°C bis -40°C	0.1°C	± 2 °C	3
Universal testing machine	Shimadzu AGS-X Std 10kNI33065534402	0-1000 mm	0.001 mm	± 0.1% (0.01 mm s<10 mm)	3
Load cell	Load cell AGS-X 500N 29152386	± 500 N	Class 1 1/500	± 1%	3
Universal testing machine	Shimadzu AG-X 50kNI3304701042	0 - 1060 mm	0.001 mm	± 0.1% (0.01 mm s<10 mm)	3
Load cell	Load cell AG-X 500N N806704	± 500 N	Class 1 1/1000	± 1%	3
Load cell	Load cell AG-X 5kN P202503	± 5 kN	Class 1 1/500	± 1%	3
Load cell	Load cell AG-X 50kN N060502	± 50 kN	Class 1 1/1000	± 1%	3
Testing pendulum	4a impetus002-BJ06-G3M4	bis 25 J,4 m/s und 2 kg	< 2%	± 1%	1
Testing pendulum	4a impetus011-BJ15-G6M6	bis 50 J,4 m/s und 3 kg	< 2%	± 1%	1
Testing pendulum	IMPETUS017-BJ18-G7M8	bis 50 J,4 m/s und 3 kg	< 2%	± 1%	1
Scalable load cell	HBM 1-CFT/20 kN	0 - 20 kN	Class 0.5	0.1%	1
Acceleration sensor	ASC 4211LN-005	± 5g	1/100	± 1%	1
Acceleration sensor	ASC 4211LN-025	± 25g	1/100	± 1%	1
Acceleration sensor	ASC 4211LN-050	± 50g	1/100	± 1%	1
Acceleration sensor	ASC 4211LN-400	± 400g	1/100	± 1%	1

Table 11: Measuring equipment used