# 4a test packages

thermoplastic materials
setups & measurement definition

**VALIMAT**

**IMPETUS**

excellence in ..

from test to material card

efficient dynamic testing for

plastics, foams, composites, …

# *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.

**Please find link to our ISO 9001 certificate under**

https://www.4a-engineering.at/downloads/cert_18022301_mp_eng_ISO9001-en.pdf

# Content

# 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.

Thermoplastic materials:

| Material | isoP (unreinforced or talkum reinforced plastic) | | | | frP (fiber reinforced plastic) | | | |
|---|---|---|---|---|---|---|---|---|
| Package | *basic* | *standard + temperature* | | *professional* | *basic* | *standard + temperature* | | *professional* |
| Material cards | 1 | 1 | 2 | 1 | 2 | 2 | 4 | 1 |
| Temperature | 23°C | 23°C | -30°C & 80°C | 23°C | 23°C | 23°C | -30°C & 80°C | 23°C |
| Static bending | 2 | 2 | 4 | 2 | 2 | 2 | 8 | 2 |
| Dynamic bending | 3 | 3 | 4 | 3 | 6 | 6 | 8 | 6 |
| Dynamic tension bending | | 1 | | 1 | | | | |
| Static tensile test | | 1 | 2 | 1 | | 2 | | 2 |
| Dynamic tensile test | | | | 1 | | | | 2 |
| Static puncture test | | | | 1 | | | | 1 |
| Dynamic puncture test | | 1 | 2 | 1 | | 1 | 2 | 1 |
| Static component test | | | | 1 | | | | 1 |
| Dynamic compnent test | | | | 1 | | | | 1 |
| Repetitions | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Measurements | 25 | 40 | 60 | 60 | 40 | 55 | 90 | 80 |
| Remark | | Detailed testing at 23°C | | | Orientation 0° & 90° | Orientation 0° & 90° | | |

| strain rate/hardening | compression/tension-asymmetry | damage/failure | validation on component |
|---|---|---|---|

## 2   Sampling – general

All specimens are generated by further processing of the standardized casting mould for injection moulding, henceforth referred to as "4a mould", as shown in Fig.1.
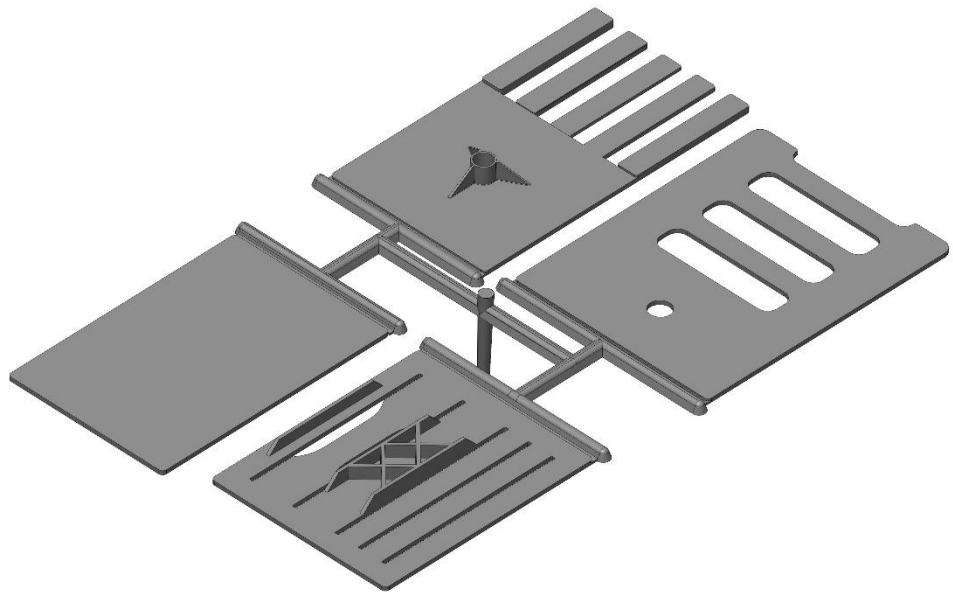


Figure 1:      4a mould

It consists of the 120x80x2 plate (Fig.2), the multi-specimen plate (Fig.3), the melt- & weld line plate (Fig.4) and the Dome & finger (Fig.5) plate.



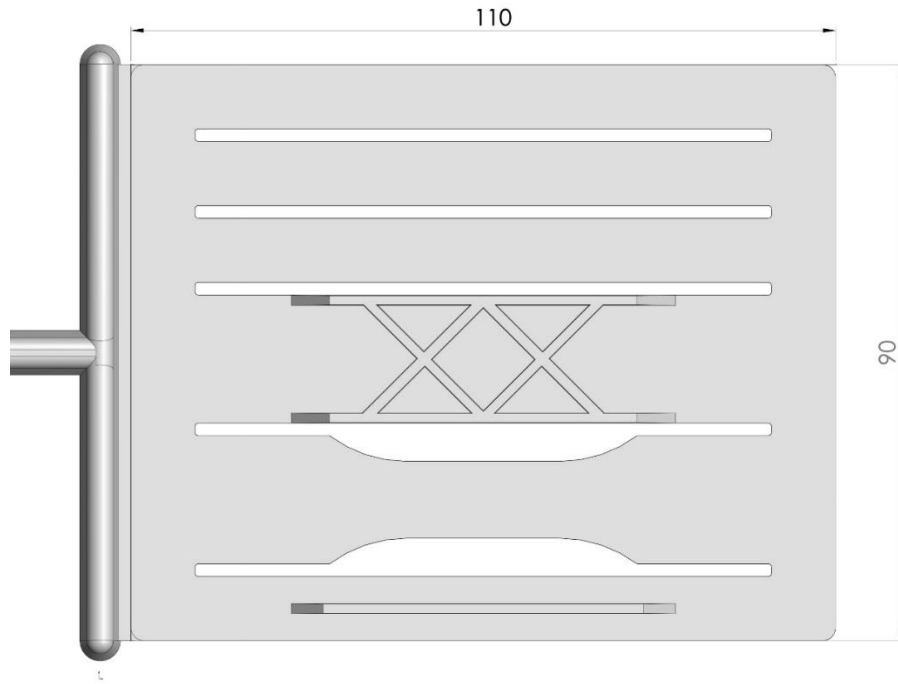Figure 2:      120x80x2 plate

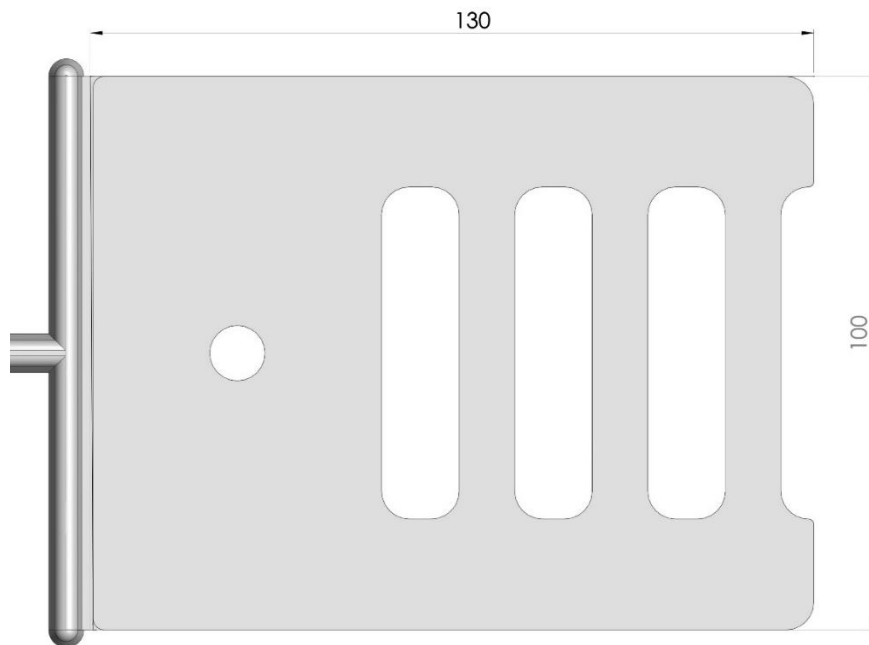Figure 3:    Multi-specimen plate
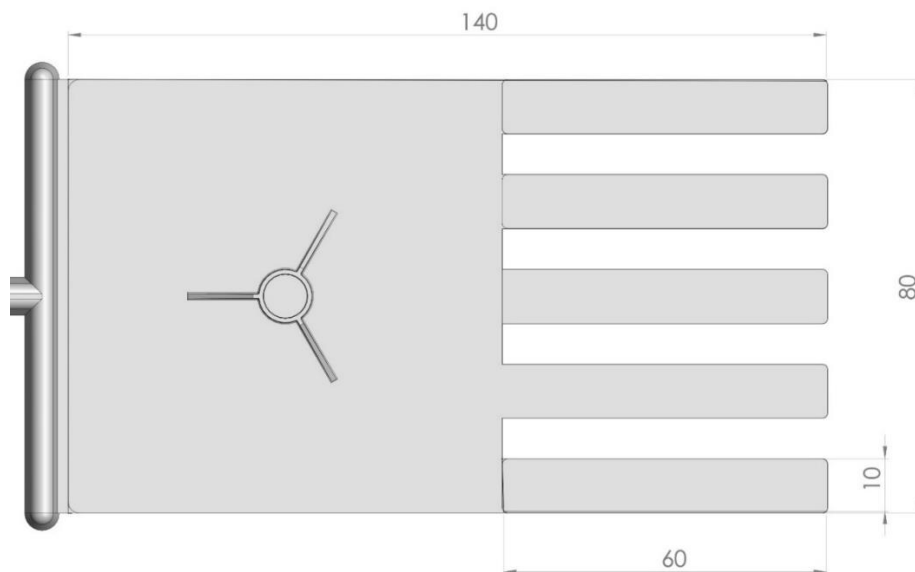
Figure 4:    Melt- & weld line plate

Figure 5:        Dome & finger plate

To achieve best quality in the production of the samples the injection moulding 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 moulding process, the specimens are each taken from defined areas within the 120x80x2 plate. Differentiating between longitudinal – 0° (Fig.6), transversal – 90° (Fig.7), diagonal – 45° (Fig.8) and average – 30° (Fig.9). 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 mould number, consecutively defined during the injection mould 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 Fig.6 and Fig.7. 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
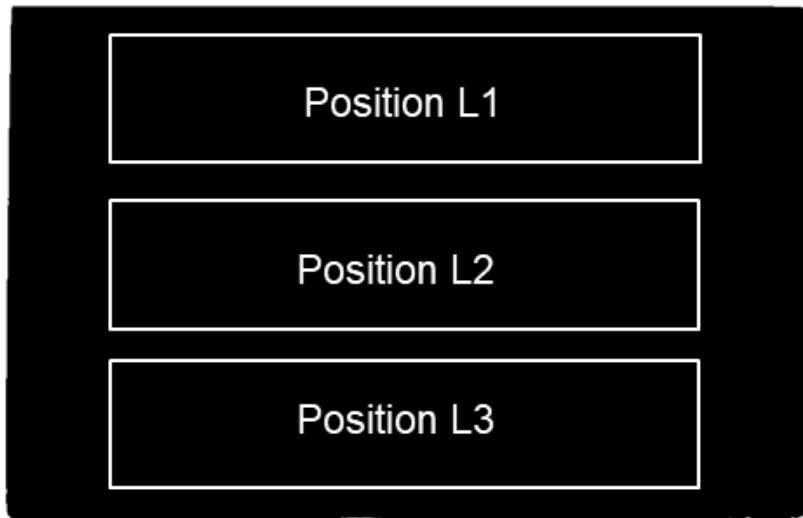
Position L1

Position L2

Position L3

Figure 6: Areas of the 120x80x2 plate for milling 0° specimen, each square measures at 90x20. The arrow indicates the flow direction

## T - transversal

Position T1

Position T2

Position T3
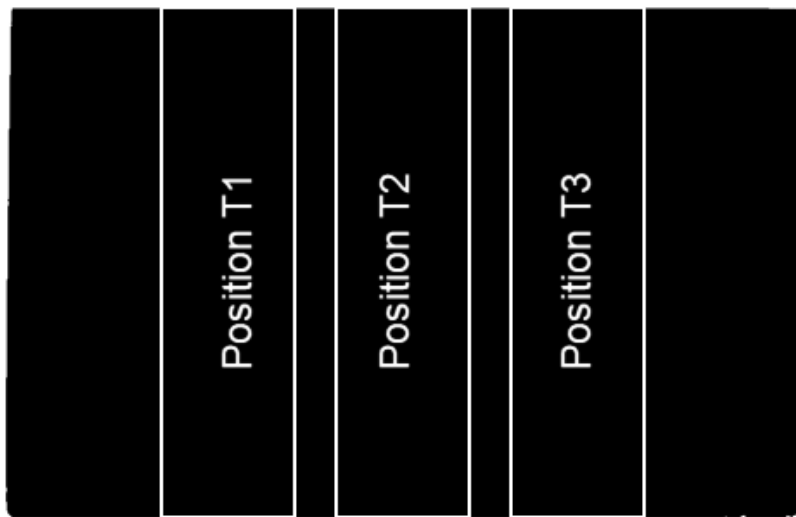
Figure 7: Areas of the 120x80x2 plate for milling 90° specimen, each square measures at 80x20. The arrow indicates the flow direction

# D - diagonal
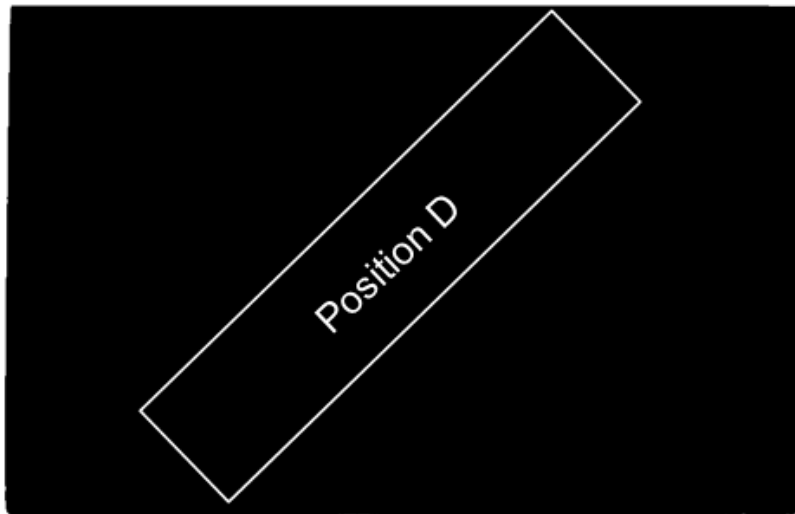


Figure 8:    Area of the 120x80x2 plate for milling 45° specimen, the square measures at 90x20. The arrow indicates the flow direction

# A - average



Figure 9:    Area of the 120x80x2 plate for milling 30° specimen, the square measures at 90x20. The arrow indicates the flow direction

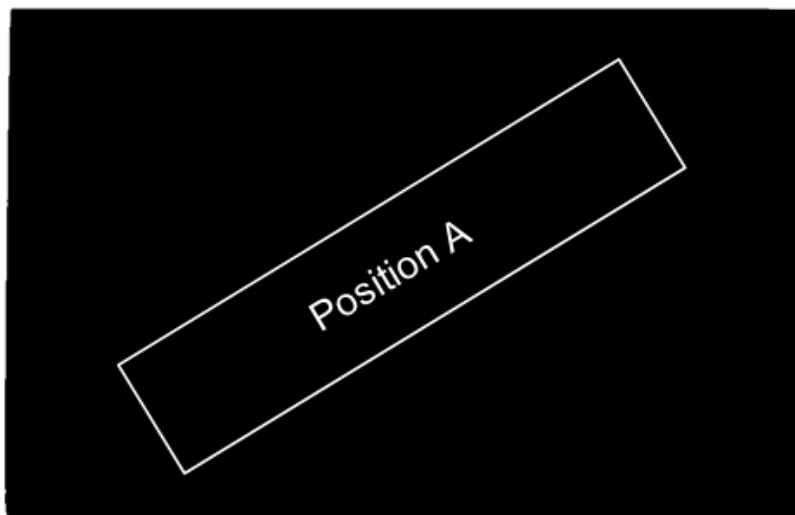All processed specimen edges are polished/grinded with a 600-grit sandpaper to prepare them for the material tests. Specimens are visually controlled and are discarded if they show any flaws on the surface, such as pits, scratches or shrink marks.

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, moulded 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 moulded 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 tempered

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 Fig.10. 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 10:     Static tempered measurements

## 3.2 Dynamic tempered

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 temperature magazine is illustrated on Fig. 11. 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 11:     4a temperature 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 the 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 to 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 moulded specimens are used, which are sawed off directly from the multi-specimen plate, as seen in Fig.12.



Figure 12:     Standard sampling for 3PB, denomination as shown.

## 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 to different specimen geometries. The fin is connected to a 500N load cell (specified in 11.2). The setup is illustrated in Fig.13.
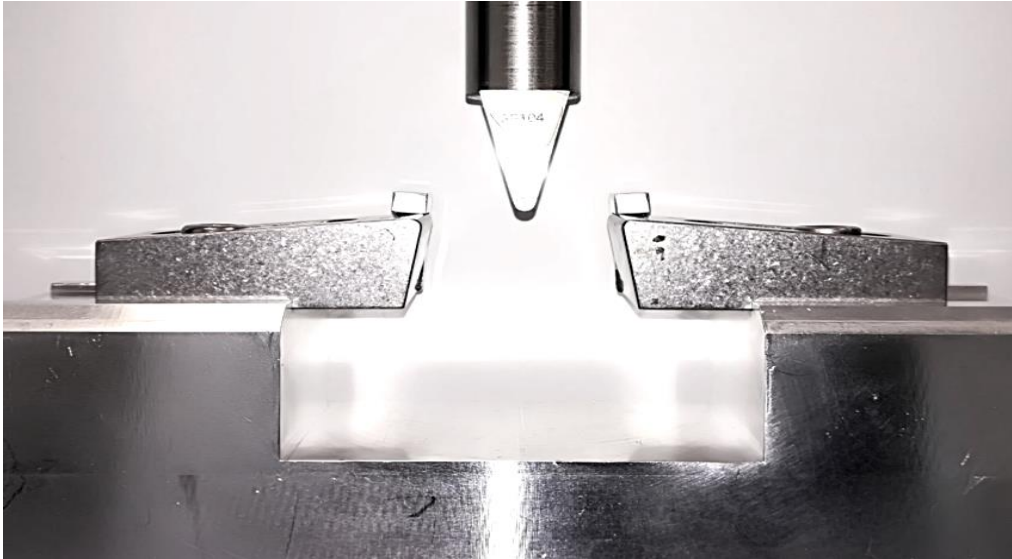
Figure 13:     Static 3PB Setup

To guide the tester during the central placement of the specimen, a magnetic L-shaped support element is used as shown Fig.14.
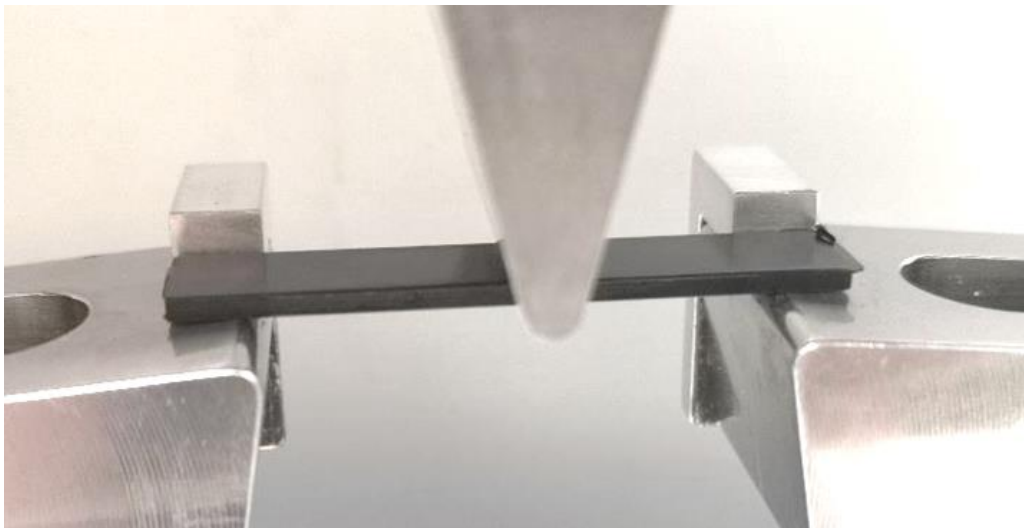


Figure 14:     Placement of the specimen

### 5.2.2   Measurement and evaluation method

Tab.1 and Tab.2 illustrate different starting strain rates $\dot{\varepsilon}^*$ resulting from different geometries and different testing velocities used for carrying out the static 3PB test. Fig.15 shows the relevant specimen measurements used in Tab.1 and Tab.2.

Table 1:     Testing parameters 3PB – 2mm thickness

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

Table 2:        Testing parameters 3PB – 3mm thickness

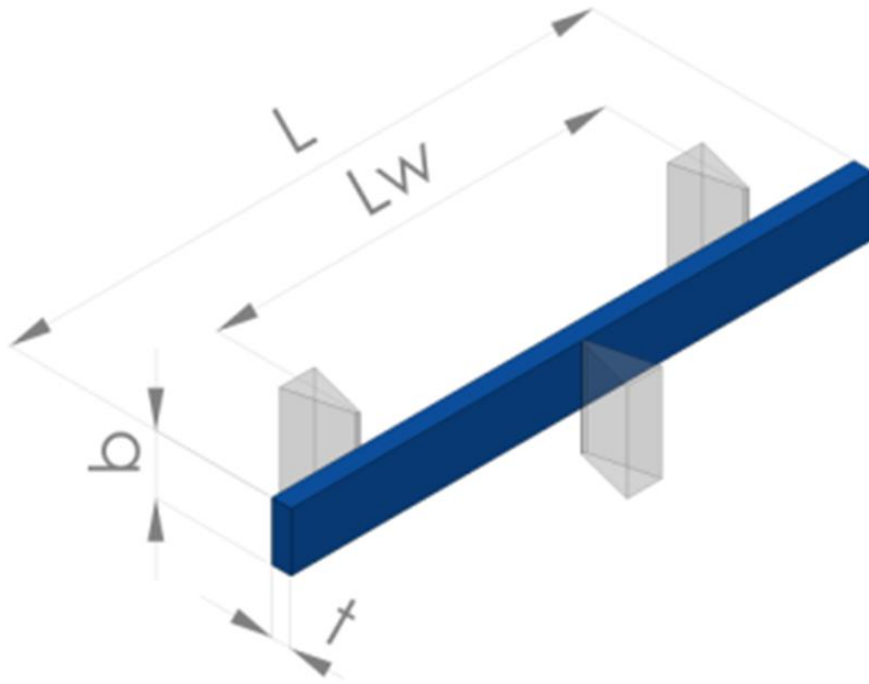| Test-Setup | $v_0$ [m/s] | $l_w$ [mm] | b [mm] | t [mm] | l [mm] | $\acute{\varepsilon}$ * [1/s] |
|---|---|---|---|---|---|---|
| stat_low | 0.0001 | 50 | 10 | 3 | 60 | 0.0007 |
| stat_high | 0.001 | 50 | 10 | 3 | 60 | 0.0072 |



Figure 15:        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 Fig.16.
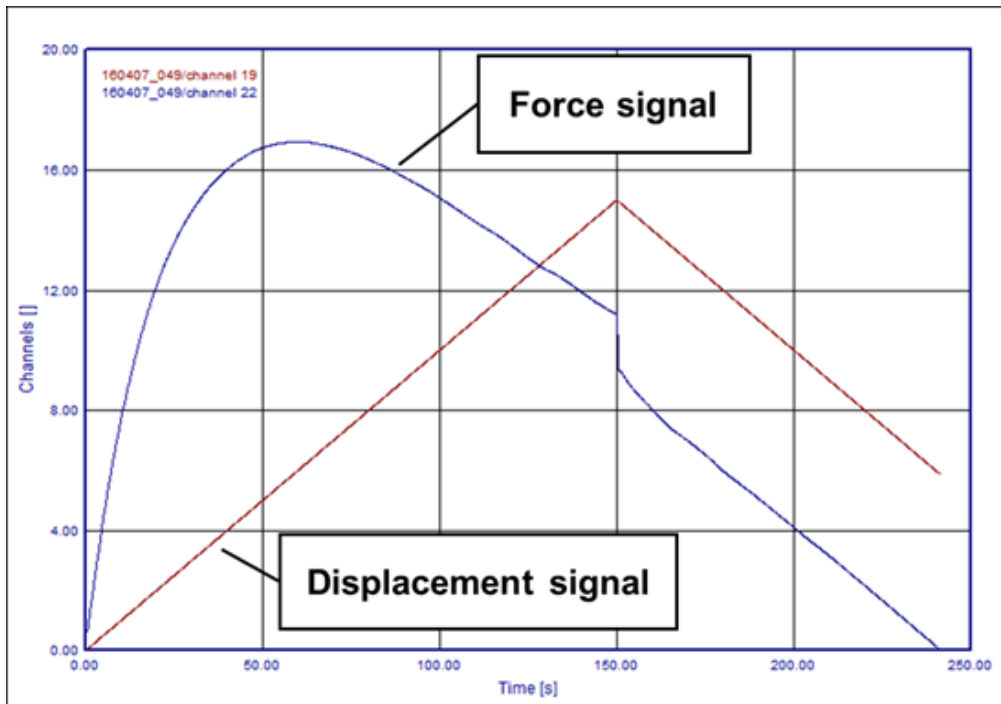
Figure 16:     Example results for force and displacement of a static 3PB test

Based on the bending beam theory (assumption: Bernoulli Hypothesis, linear elastic) the outer-fibre stress $\sigma$, strain $\varepsilon$ 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 Fig.17.
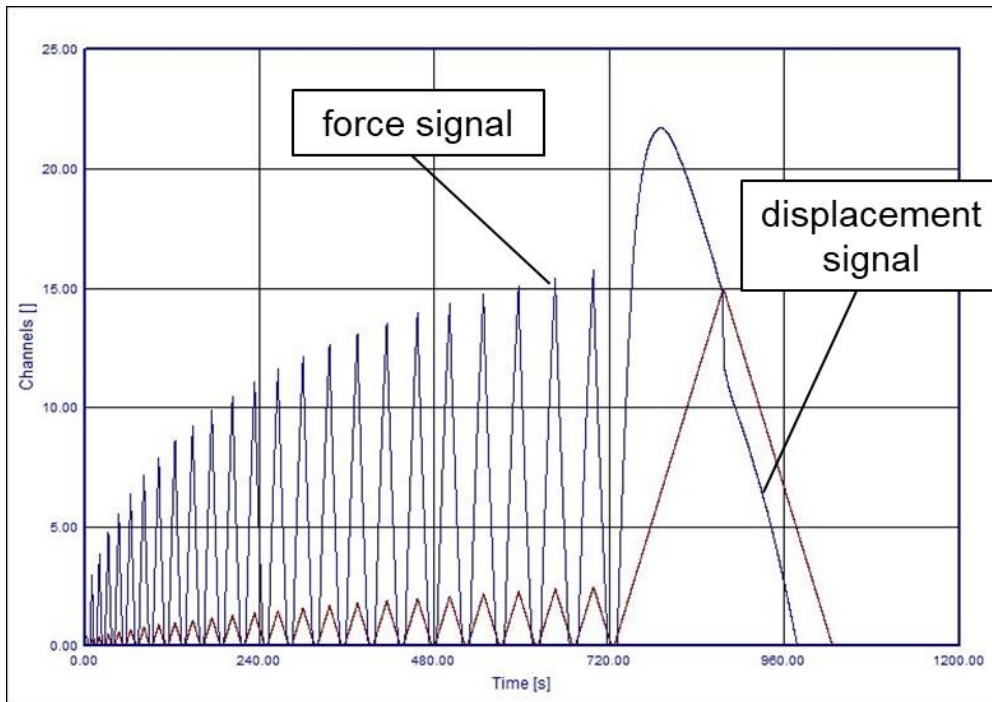
Figure 17:    Example result for force and displacement of a cyclic 3PB

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 Fig.18.
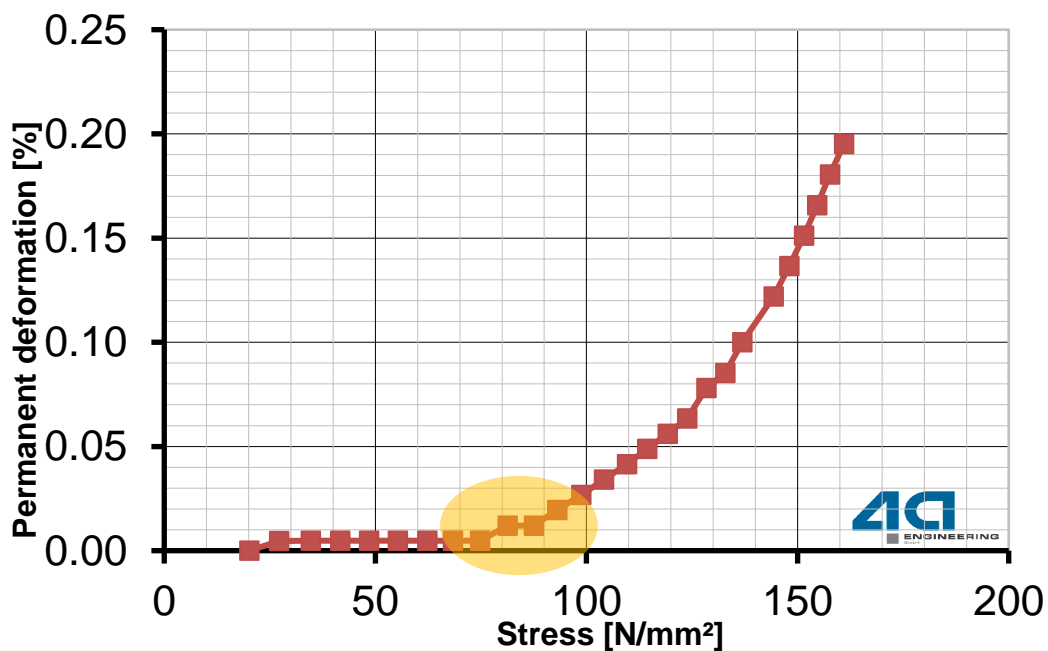


Figure 18:    Example evaluation of a cyclic 3PB, the marked area implicates the yield limit

## 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 Fig.19.



Figure 19:     Test setup dynamic 3PB

## 5.3.2   Measurement and evaluation method

Standard test parameters are displayed in Tab.3 and Tab.4, illustrating different starting strain rates $\dot{\varepsilon}^*$. Relevant measurements are illustrated on Fig.15.

Table 3: Testing parameters dynamic 3PB – 2mm thickness

| 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 4: Testing parameters dynamic 3PB – 3mm thickness

| 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 | 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 |

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 Fig.20. Take in regard that the scatter induced in the test curves is due to dynamic swinging phenomena.
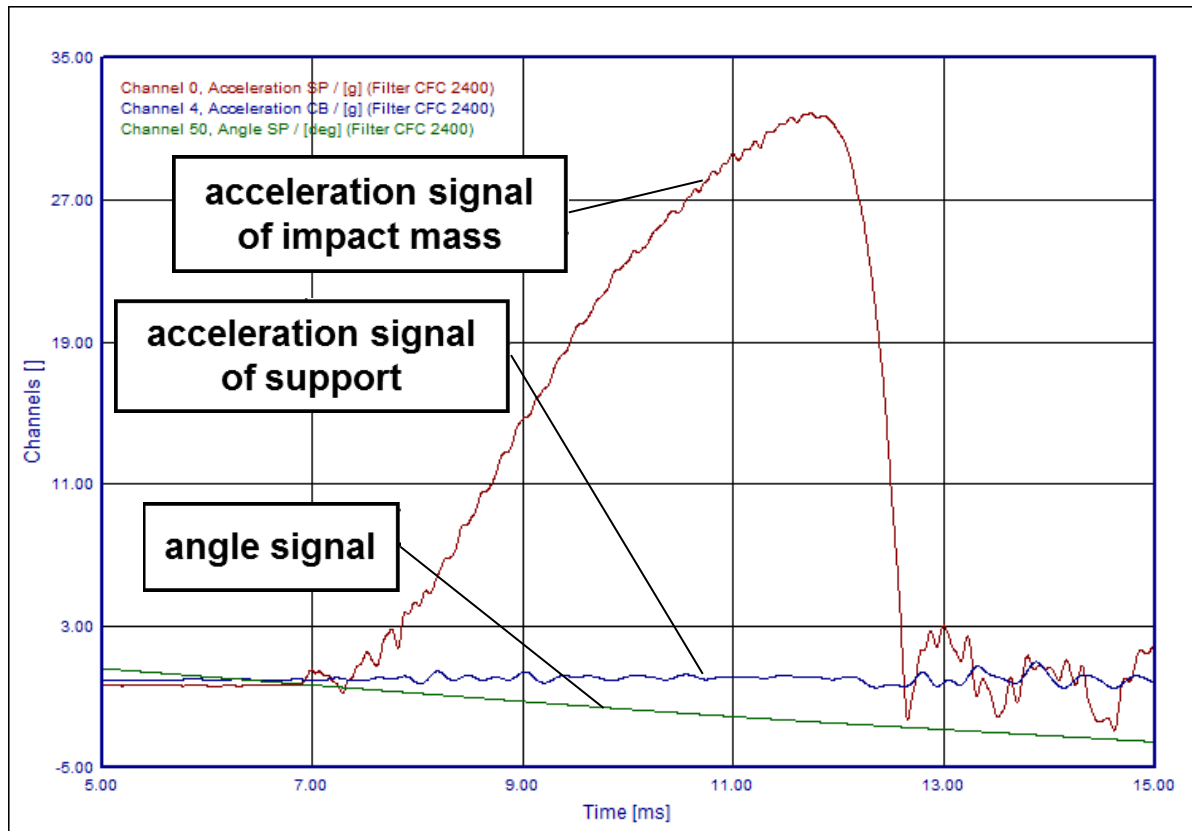


Figure 20:     Example results for acceleration and angle of a dynamic 3PB test

## 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 Fig.21.
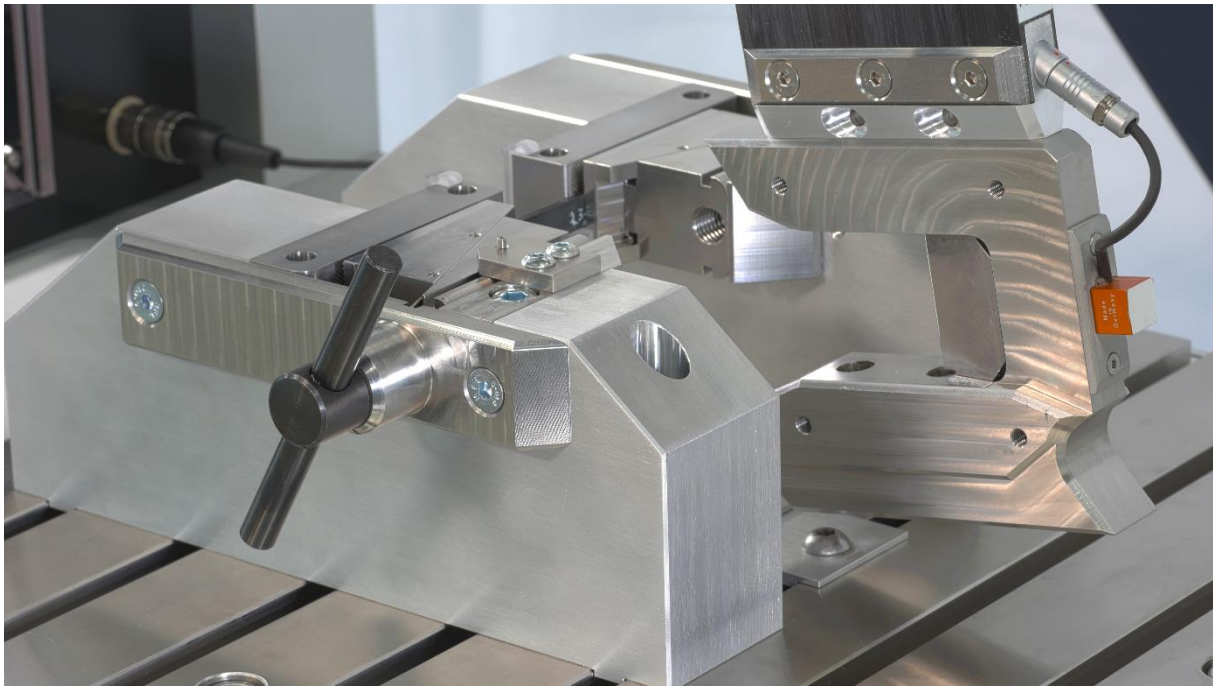


Figure 21:     Clamped 3PB setup

## 5.4.2    Measurement and evaluation method

Standard test parameters are displayed in Tab.5. Relevant specimen dimensions are depicted on Fig.22. Measurement methods are equivalent to earlier described 3PB setups.

Table 5:     Testing parameters dynamic 3PBC

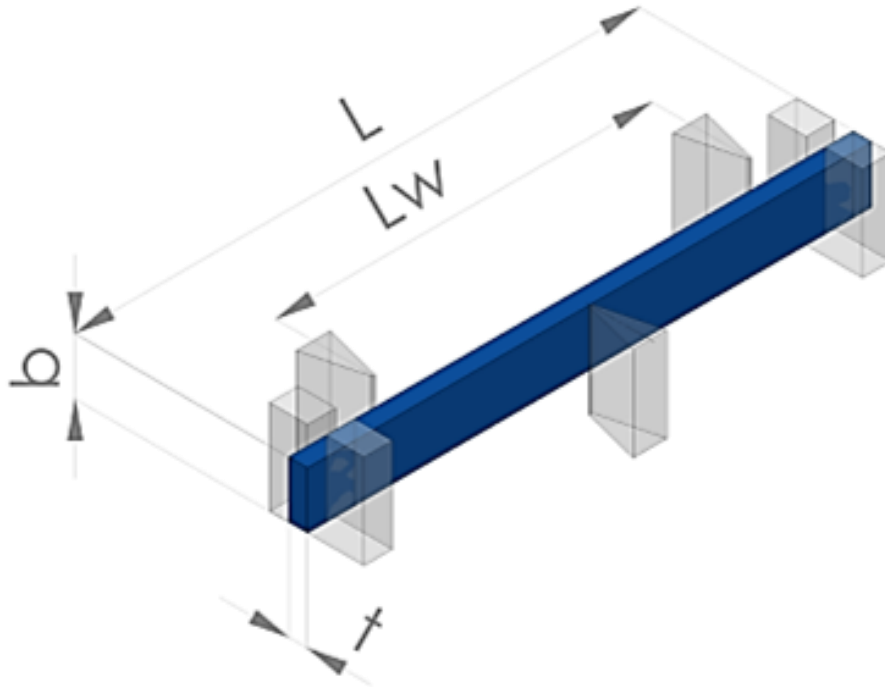| Test-Setup | $v_0$ [m/s] | $l_w$ [mm] | $m_{Pendulum}$ [g] | b [mm] | t [mm] | l [mm] |
|---|---|---|---|---|---|---|
| 3PBC | 3 | 40 | 1580 | 10 | 2 | 80 |

Figure 22:     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, milled only, Fig.23)
- IMPETUS-UT-Z24 (FRP standard, can be sawed off multi specimen plate, Fig.24)
- IMPETUS-UT-Becker (optional, Fig. 25)
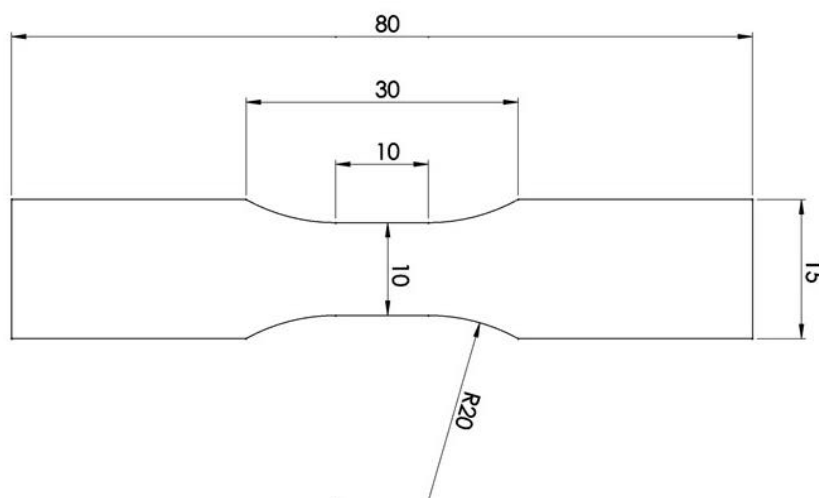- IMPETUS-UT-Junginger (optional, Fig.26)



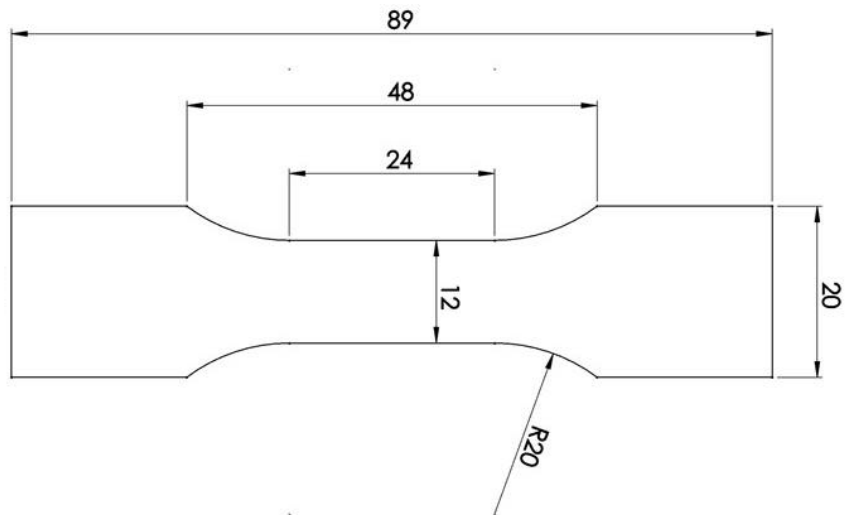Figure 23:     Geometry of IMPETUS-UT-Typ3 specimens
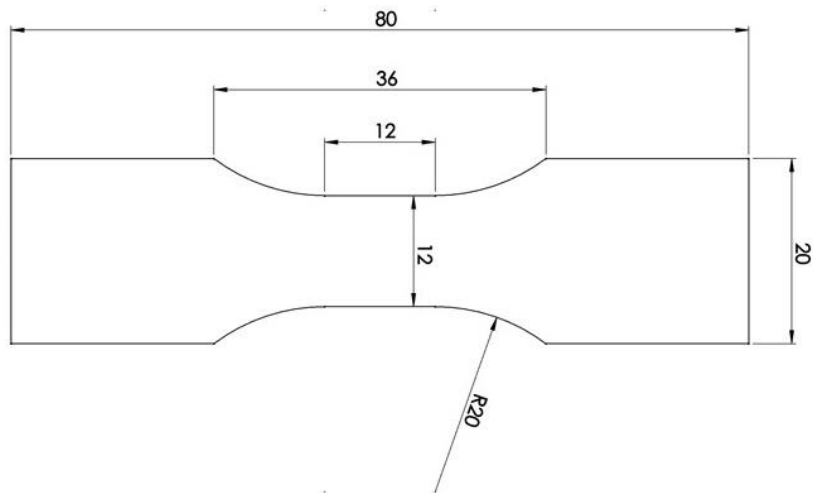
Figure 24:     Geometry of IMPETUS-UT-Z24 specimens
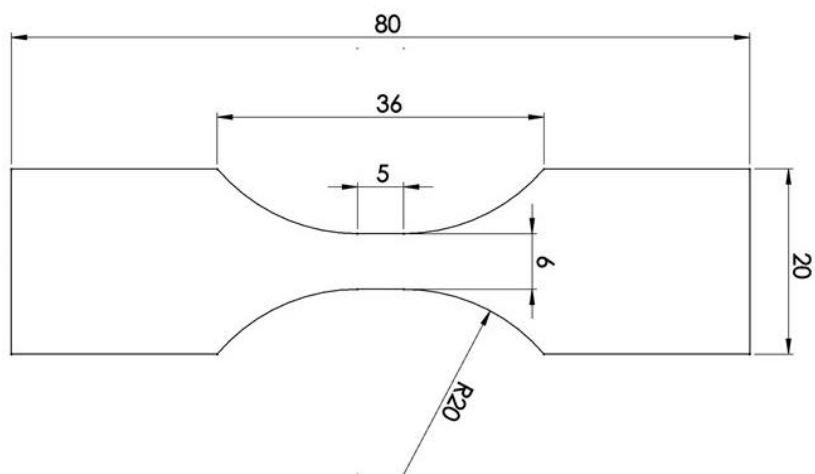


Figure 25:     Geometry of IMPETUS-UT-Becker specimens



Figure 26:     Geometry of IMPETUS-UT-Junginger specimens

## 6.2 Static testing

### 6.2.1 Setup

The static TT is conducted using a universal testing machine (Shimadzu AG-X), as illustrated in Fig.27.



Figure 27: 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 MPi, 73 fps). In dynamic measurements the high-speed camera Photron FASTCAM NOVA with a maximum resolution of 1024x1024 (1 MPi, 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 Fig.28. 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 Fig.28.
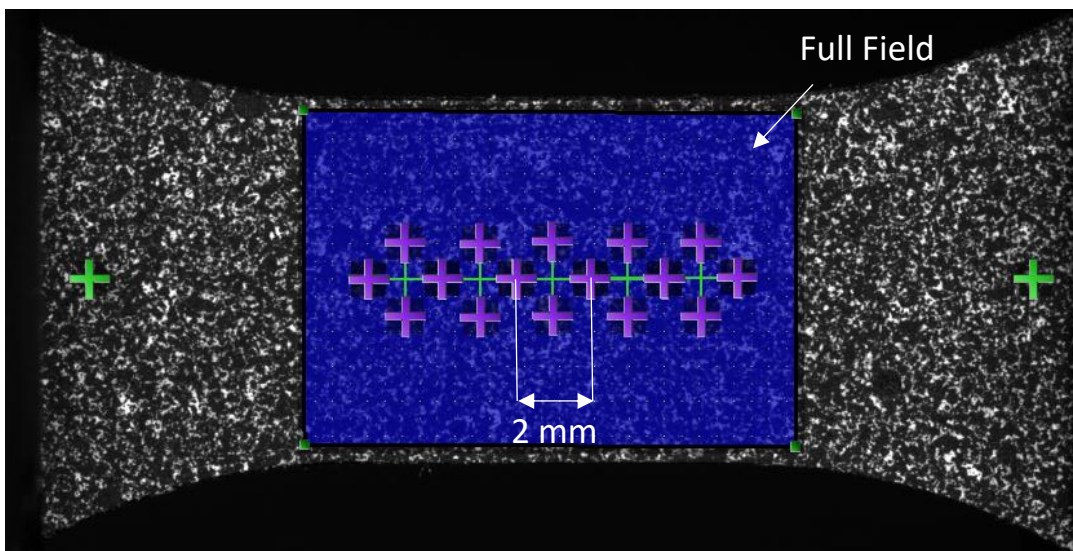


Figure 28:     Digital image correlation (DIC) strain measurement on a standard Typ3 specimen

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.

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

$\varepsilon_t$ … 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).

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

$\sigma_t$ … 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 Fig.29.
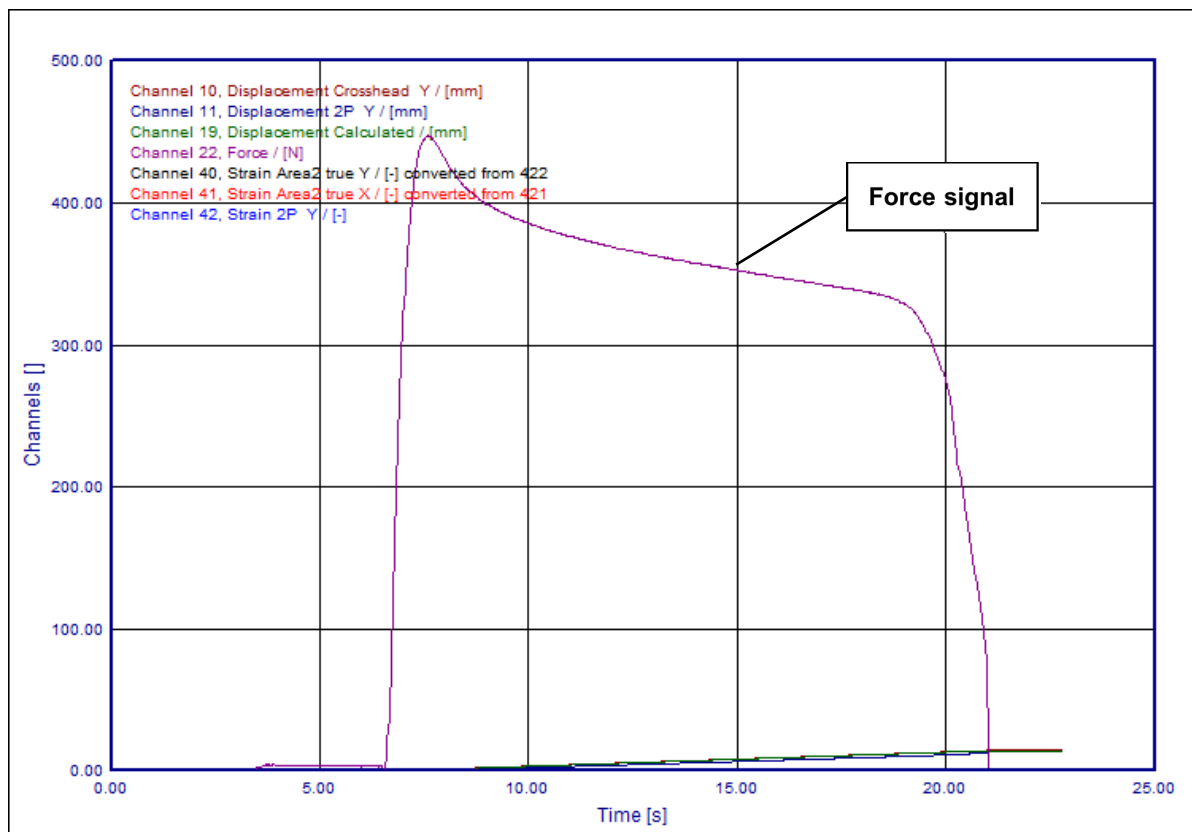


Figure 29:     Example result for force of a static TT

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 Fig.30.
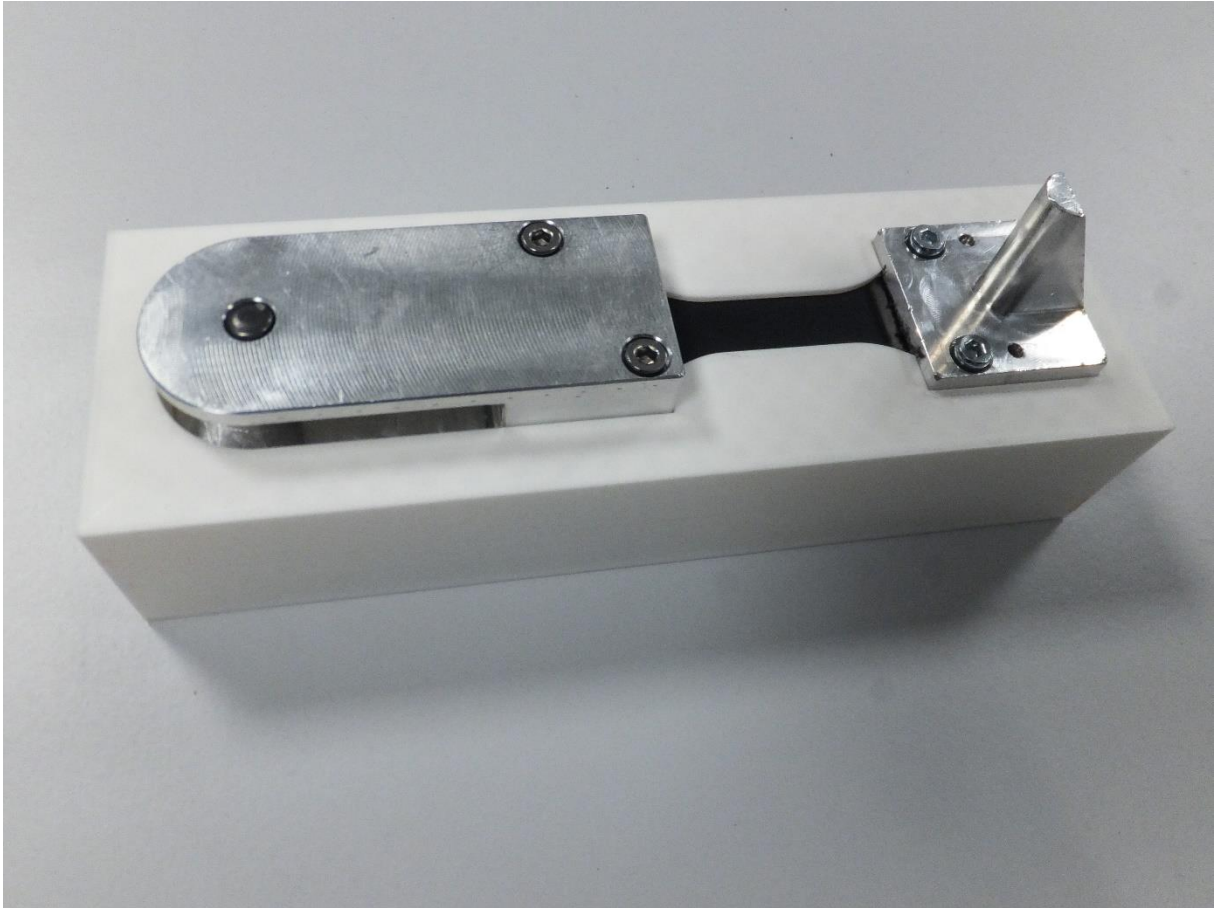
Figure 30:     Testing specimen with clamping set in placing template

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 Fig.31. After clamping the specimen, it is placed on the support bearing as pictured in Fig.32. A swing hammer mass of 3510g is used.
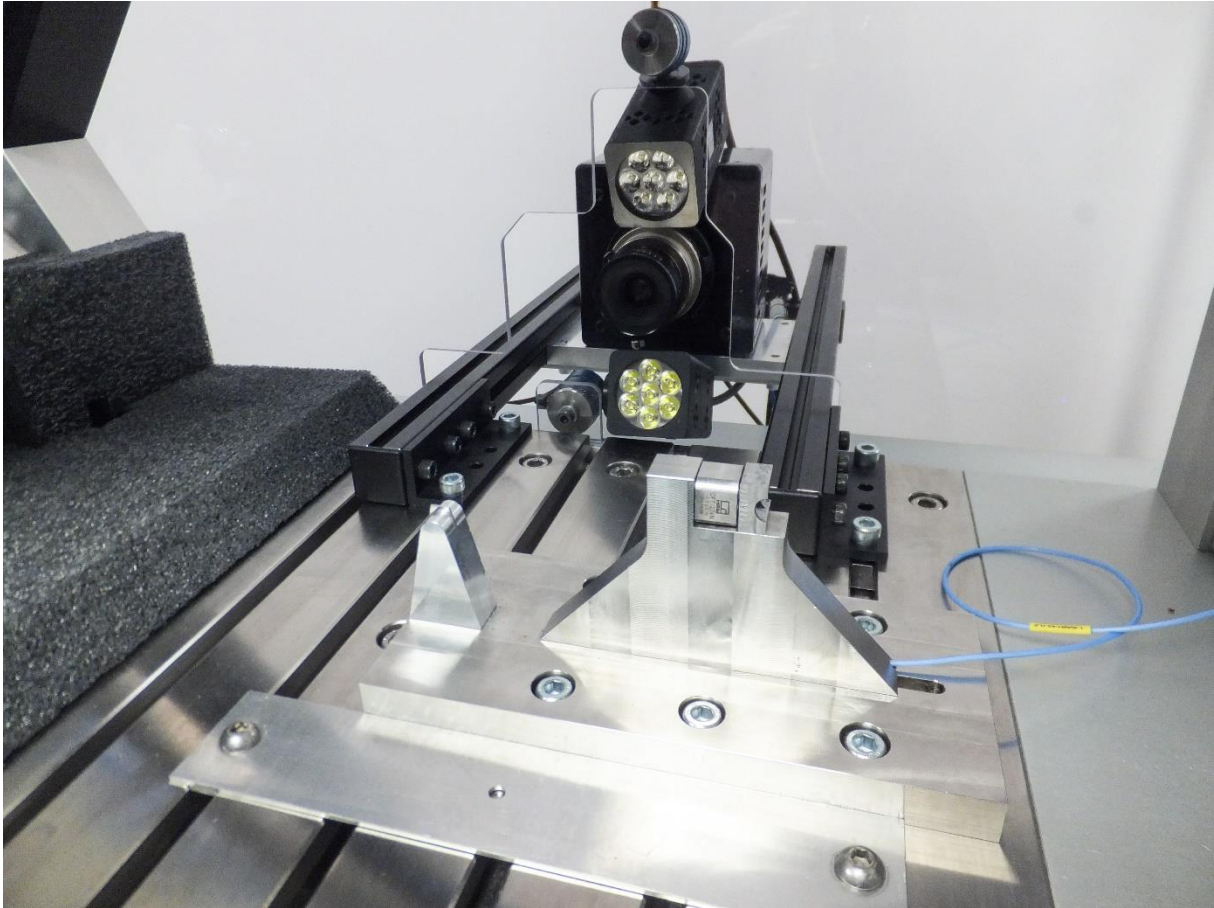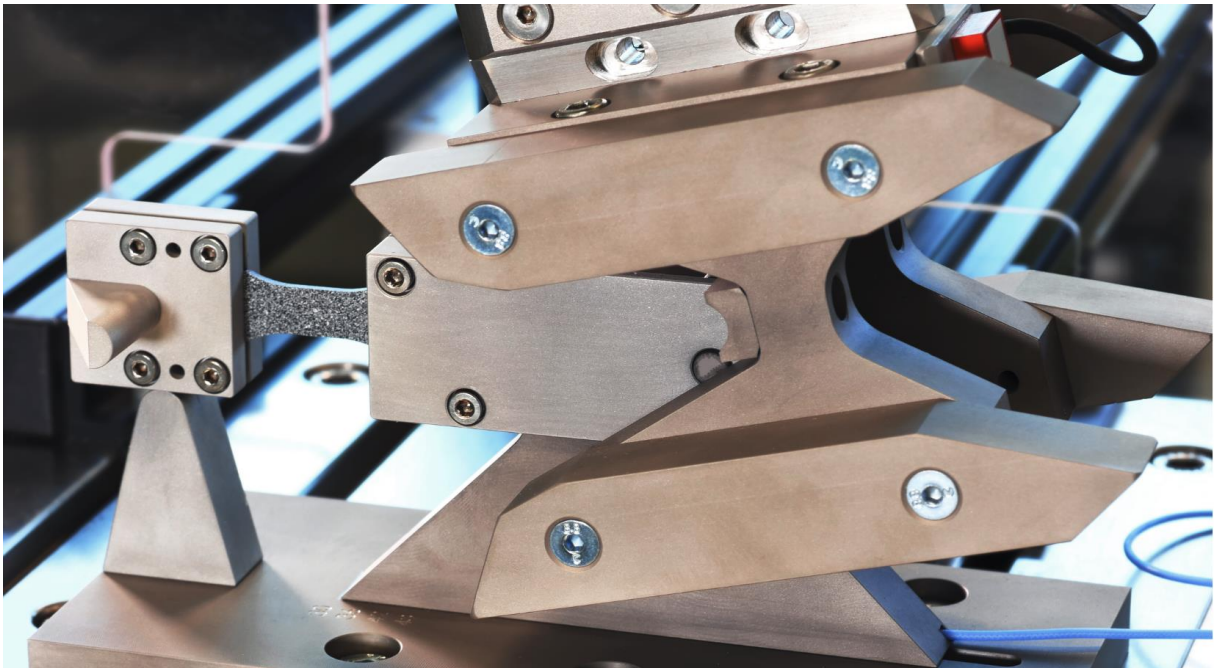
Figure 31:    Dynamic tensile test setup



Figure 32:    Specimen placed on the support bearing for the dynamic tensile test

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### 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 Fig.33. 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.
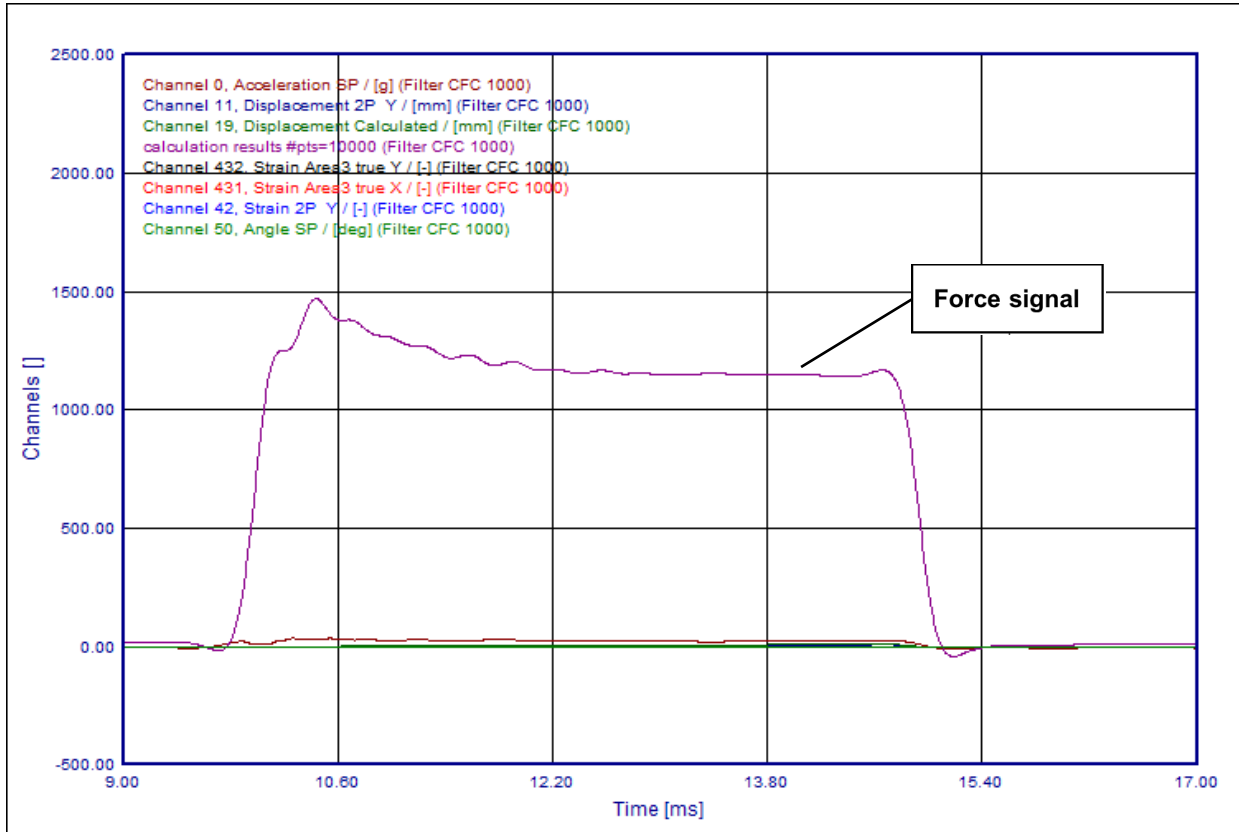


Figure 33:    Example result for force of a dynamic TT

## 7  Puncture test (PT)

### 7.1  Specimen geometry

Following specimens are used for the puncture tests:

- IMPETUS-PT-STAT-V1, 80x80x2 (static standard, Fig.34)
- IMPETUS-PT-DYN-V1, 120x80x2 (dynamic standard, Fig.35)
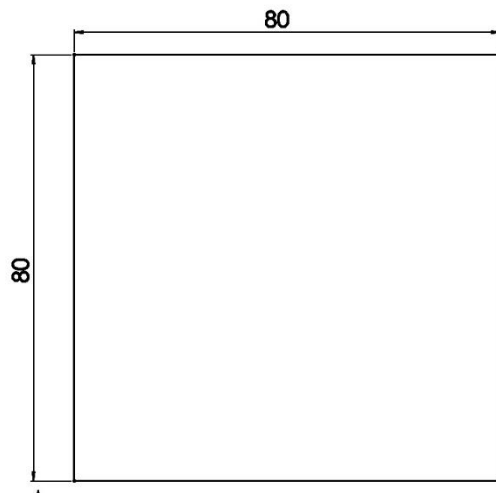
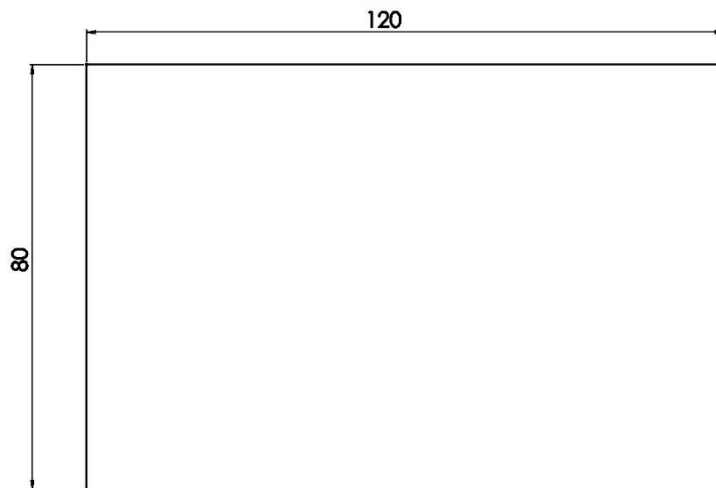Figure 34:    Standard specimen IMPETUS-PT-STAT-V1 for static puncture test



Figure 35:    Standard specimen IMPETUS-PT-DYN-V1 for dynamic puncture test

The 120x80x2 specimen is directly cut off the 4a mould, 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 Fig.36.

Figure 36:     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 Fig.37.

In the puncture test there are three distinct failing mechanism observed, which result in specific curves and breaking patterns, shown in Fig.38.

Relevant specimen measurements are depicted on Fig.39.

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

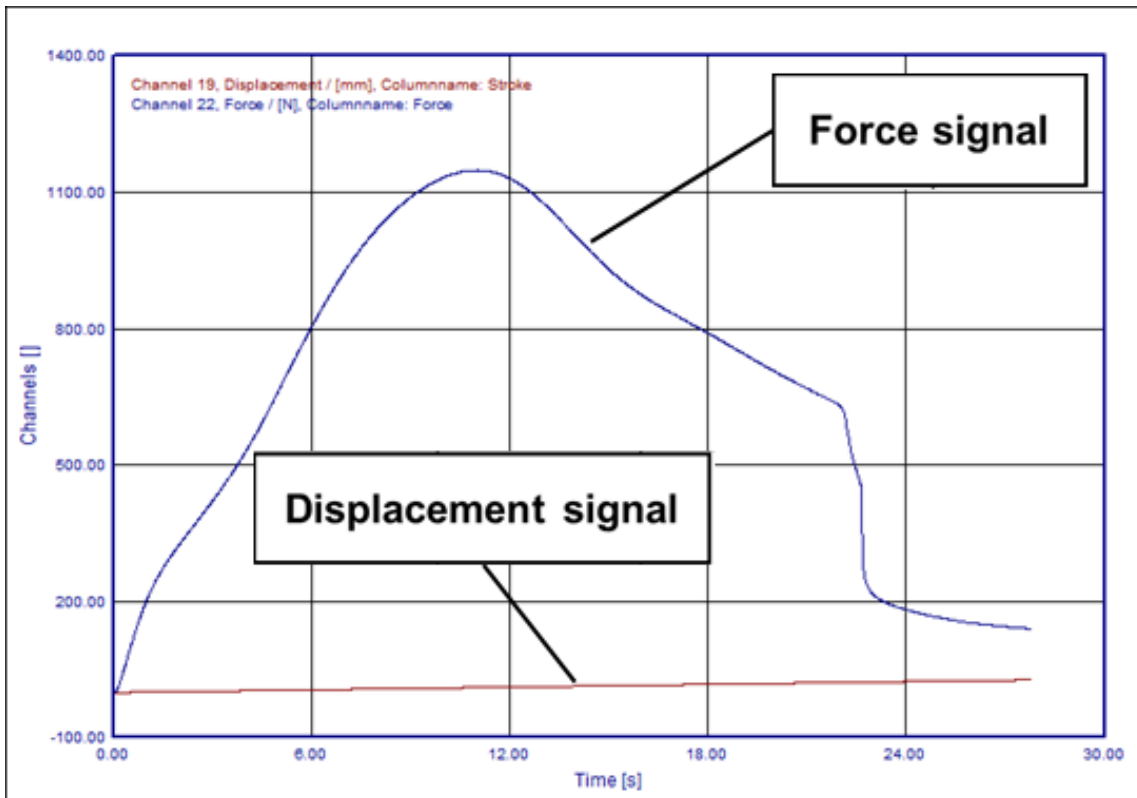Evaluation is based on ISO 6603.

Figure 37:    Example result for force and displacement of a static PT
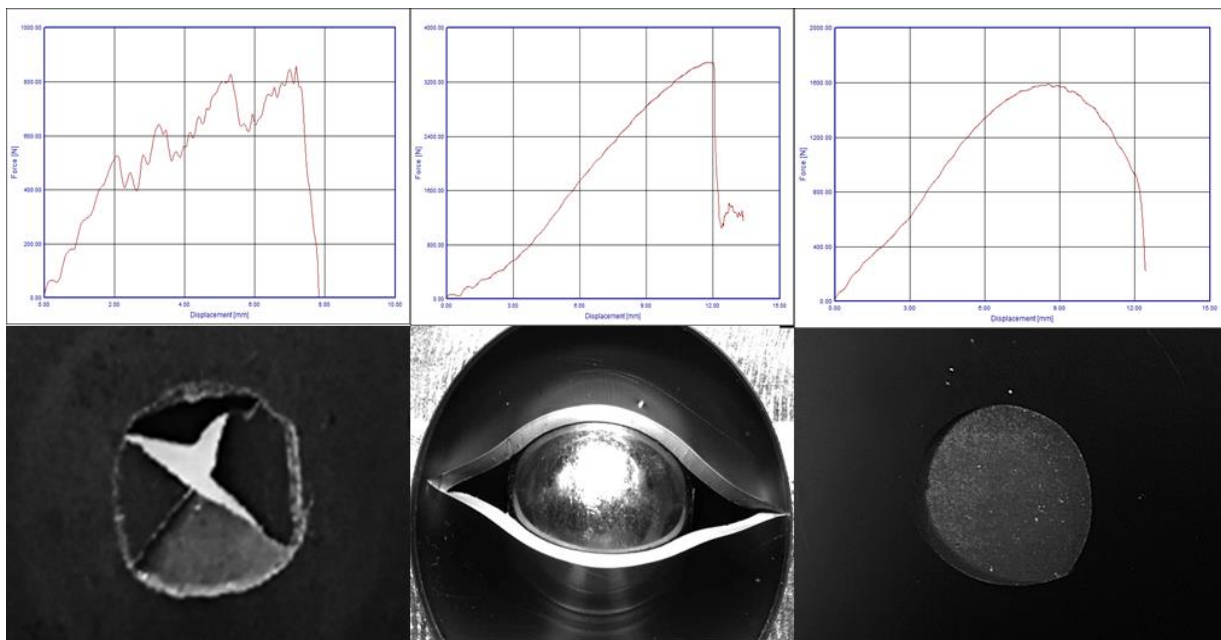


Figure 38:    Characteristic failing mechanisms PT, depending on load speed, temperature and material, from left to right: no yielding, brittle cracking; yielding and cracking; yielding and deep drawing
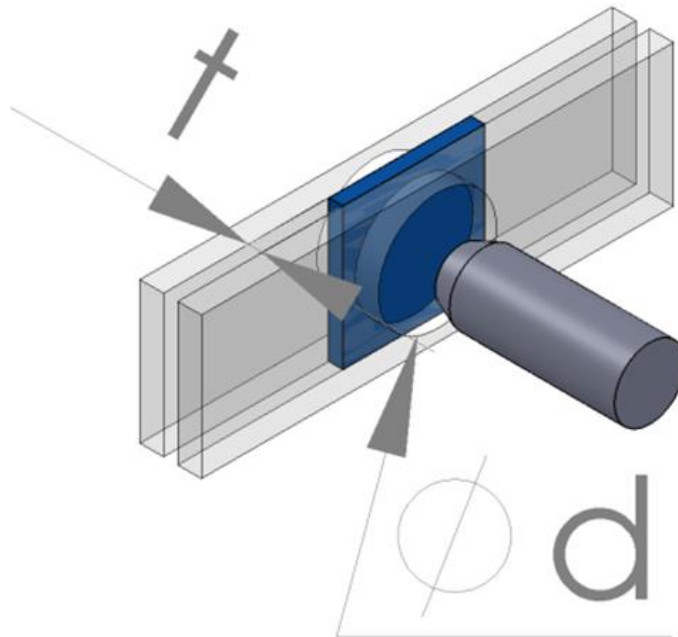
Figure 39:     Relevant specimen measurements for testing

## 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 Fig.40.
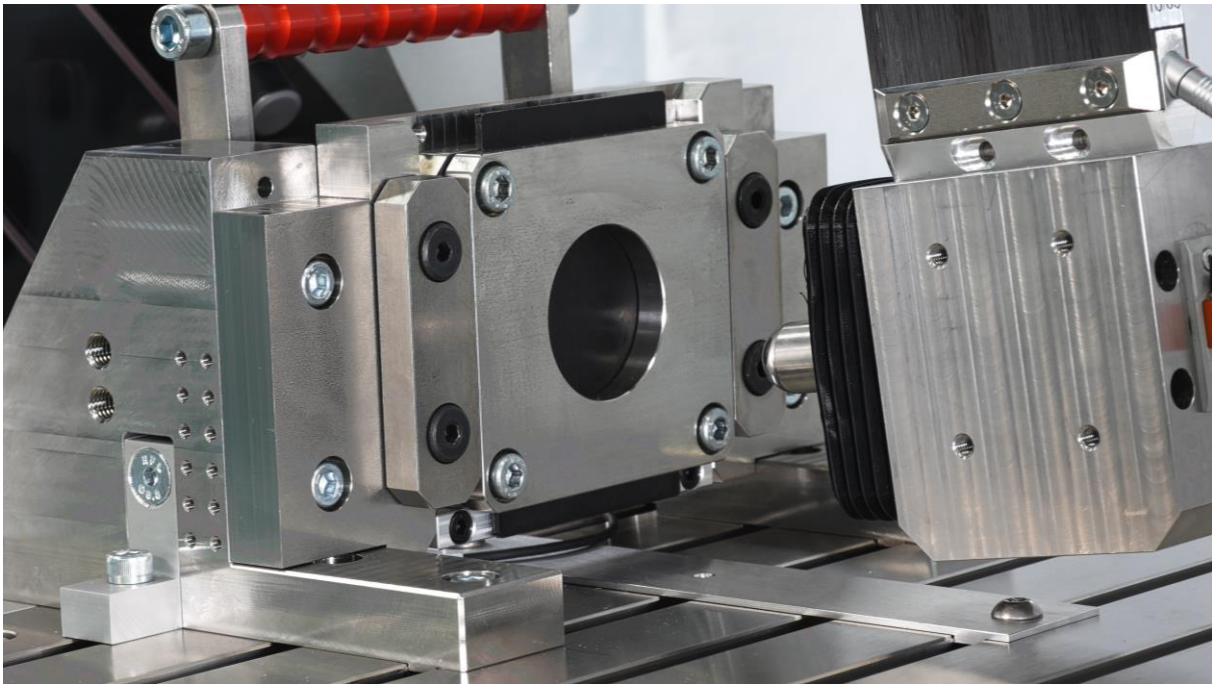
Figure 40:    Dynamic puncture test setup

## 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 Fig.39. Take in regard that the scatter induced in the test curves is due to dynamic swinging phenomena.
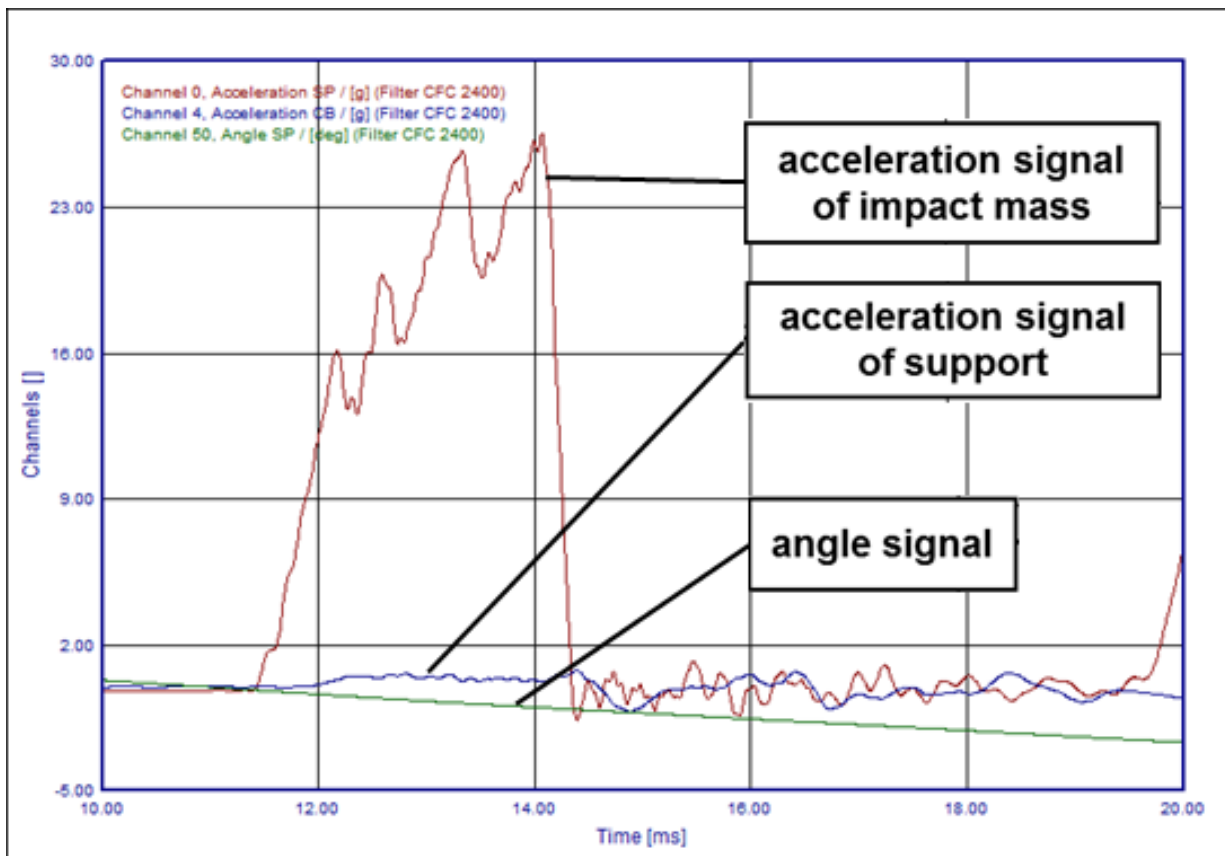


Figure 41:    Example result for acceleration and angle of a dynamic PT

# 8   Shear test (ST)

## 8.1   Specimen geometry

Following specimens are used for the shear tests:

- IMPETUS-SH-V1 ("Butterfly", optional, static only, Fig.42)
- IMPETUS-SH-V2 (ASTM-B831 modified, standard, static and dynamic, Fig.43)
- IMPETUS-SH-V3 (ASTM-B831 modified, optional, static and dynamic, Fig.44)
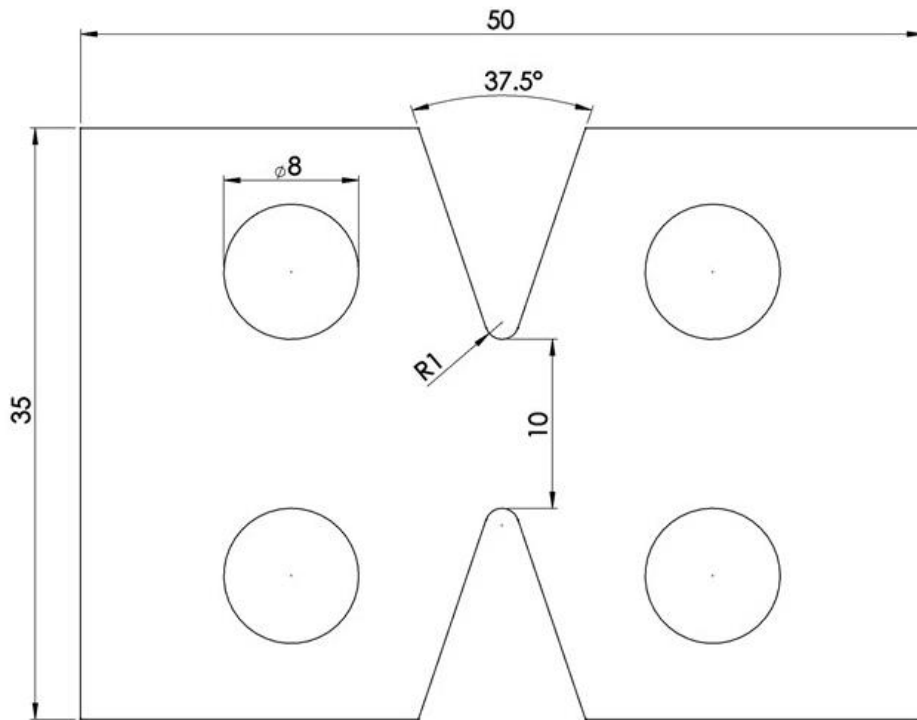


Figure 42: IMPETUS-SH-V1, optional specimen for static shear test
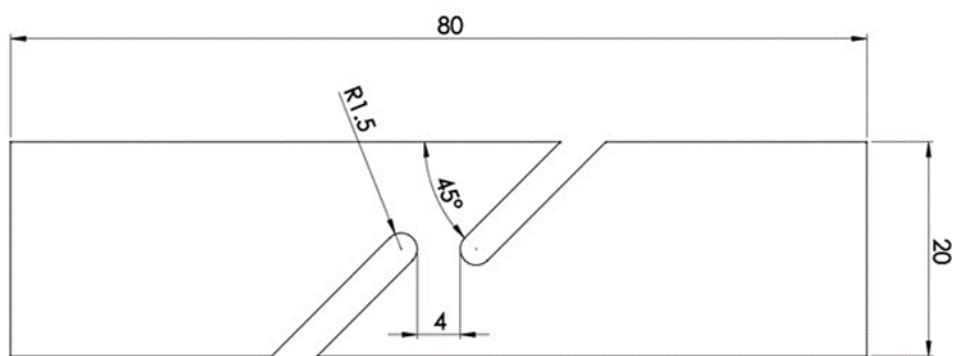


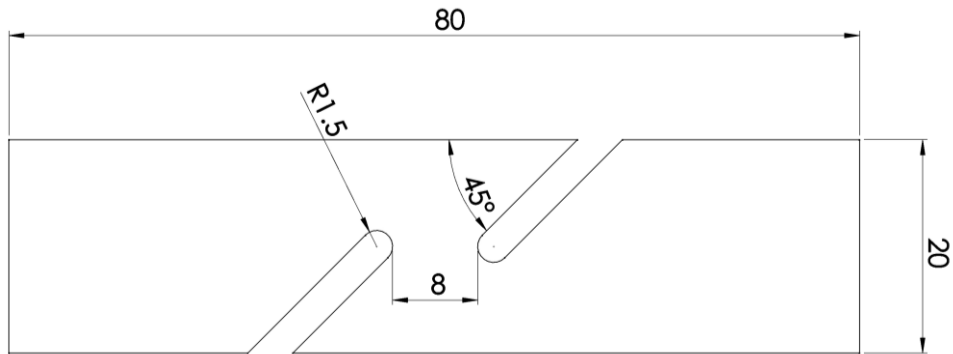Figure 43:      IMPETUS-SH-V2, standard specimen for shear test

Figure 44:    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 Fig.45.
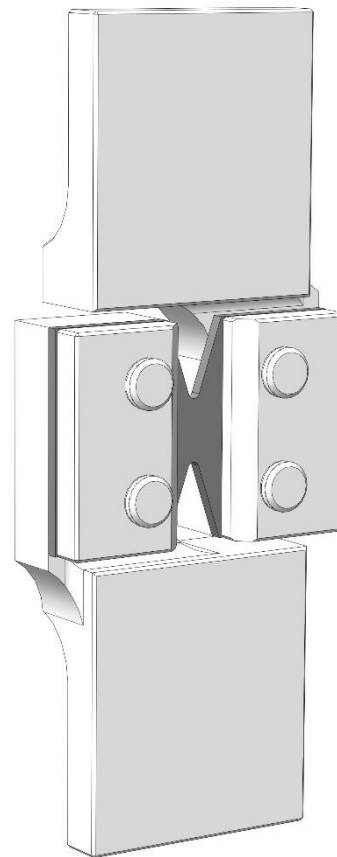
Figure 45:     Test setup for butterfly specimen, static tensile test 50kN

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 Fig.46. The force is directly measured via the loading cell. The shear strain is obtained from the DIC system, illustrated on Fig.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 Fig.47.

Table 6:     Testing parameters static ST – butterfly specimen

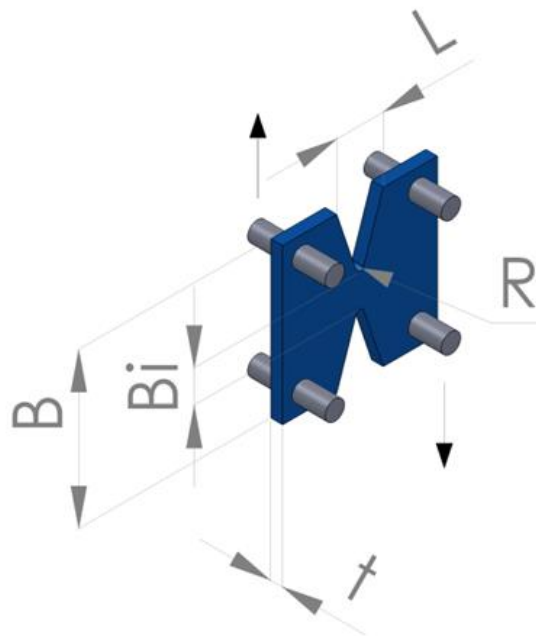| Test-Setup | $v_0$ [m/s] | L [mm] | B [mm] | $B_i$ [mm] | t [mm] | R [mm] |
|---|---|---|---|---|---|---|
| ST_stat | 0.0001 | 10 | 35 | 10 | 2 | 1 |



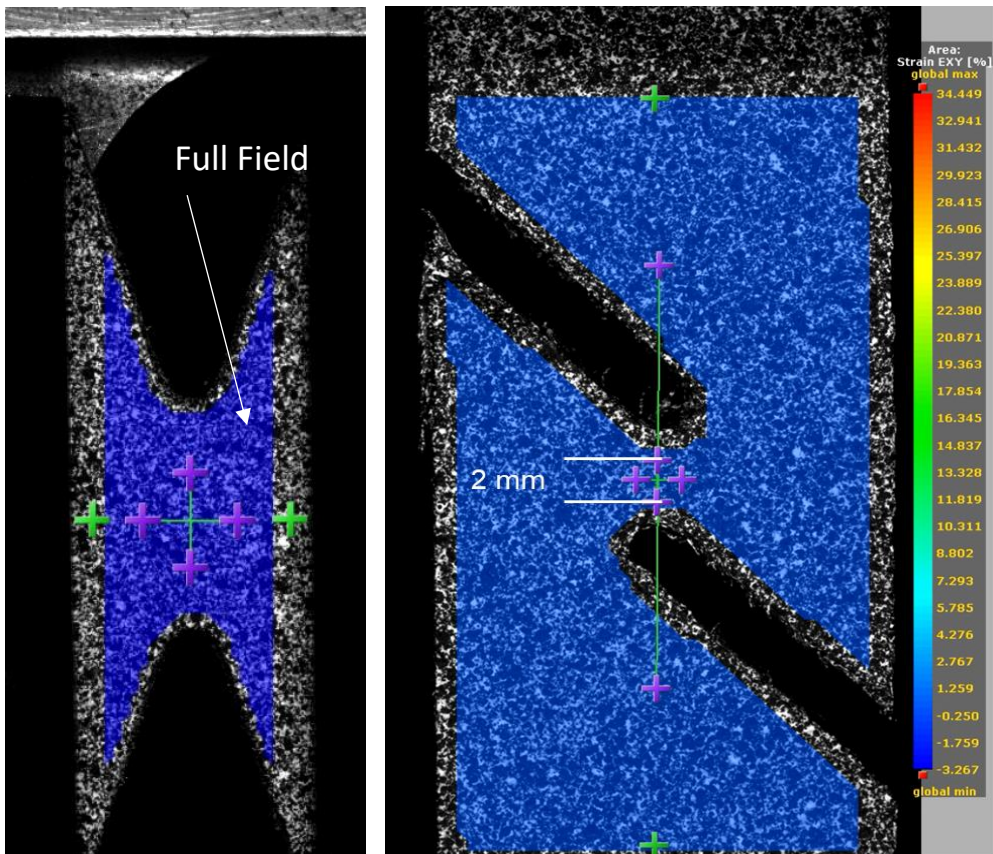Figure 46:     Relevant specimen measurements for the ST – butterfly

Figure 47: DIC measurement for ST

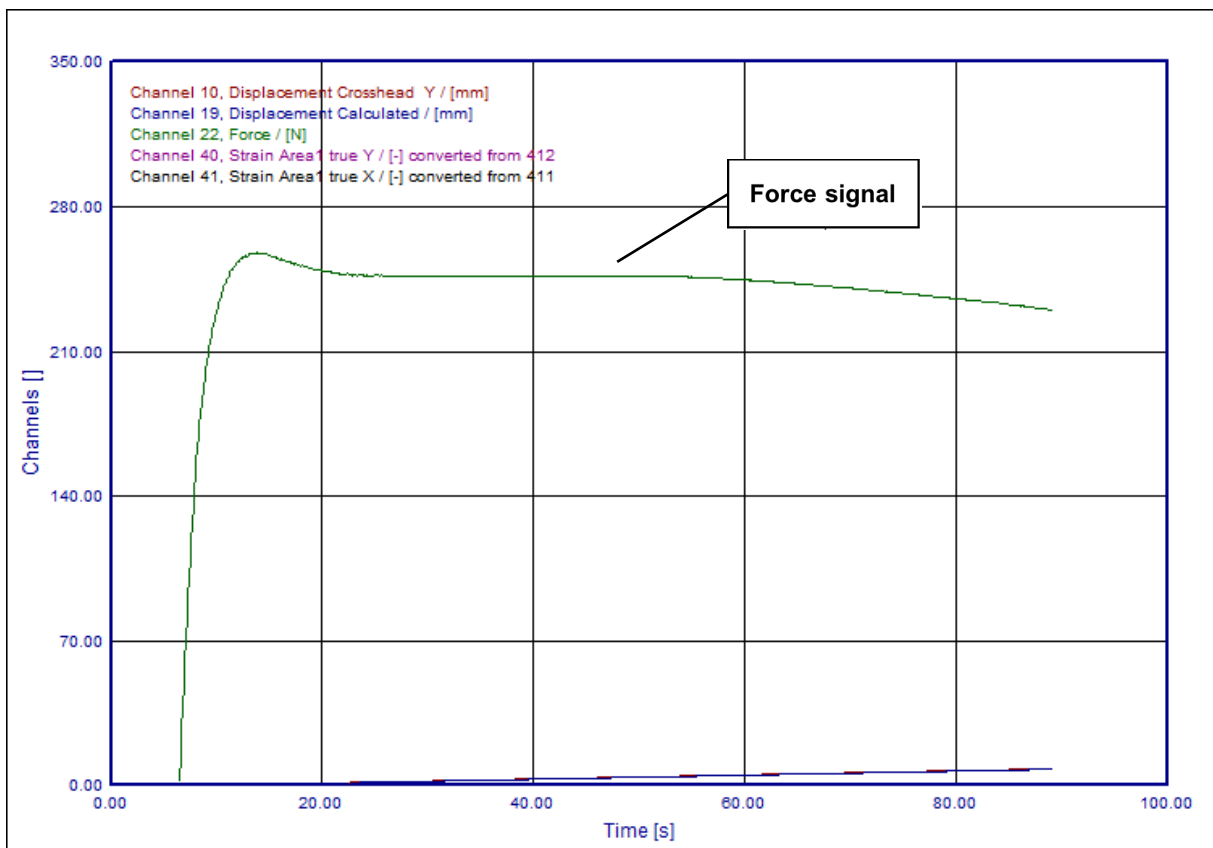A typical result of a static shear test is displayed on Fig.48



Figure 48:     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 Fig.49. Basically, the measuring is analogue to the dynamic tensile test described in 6.3.
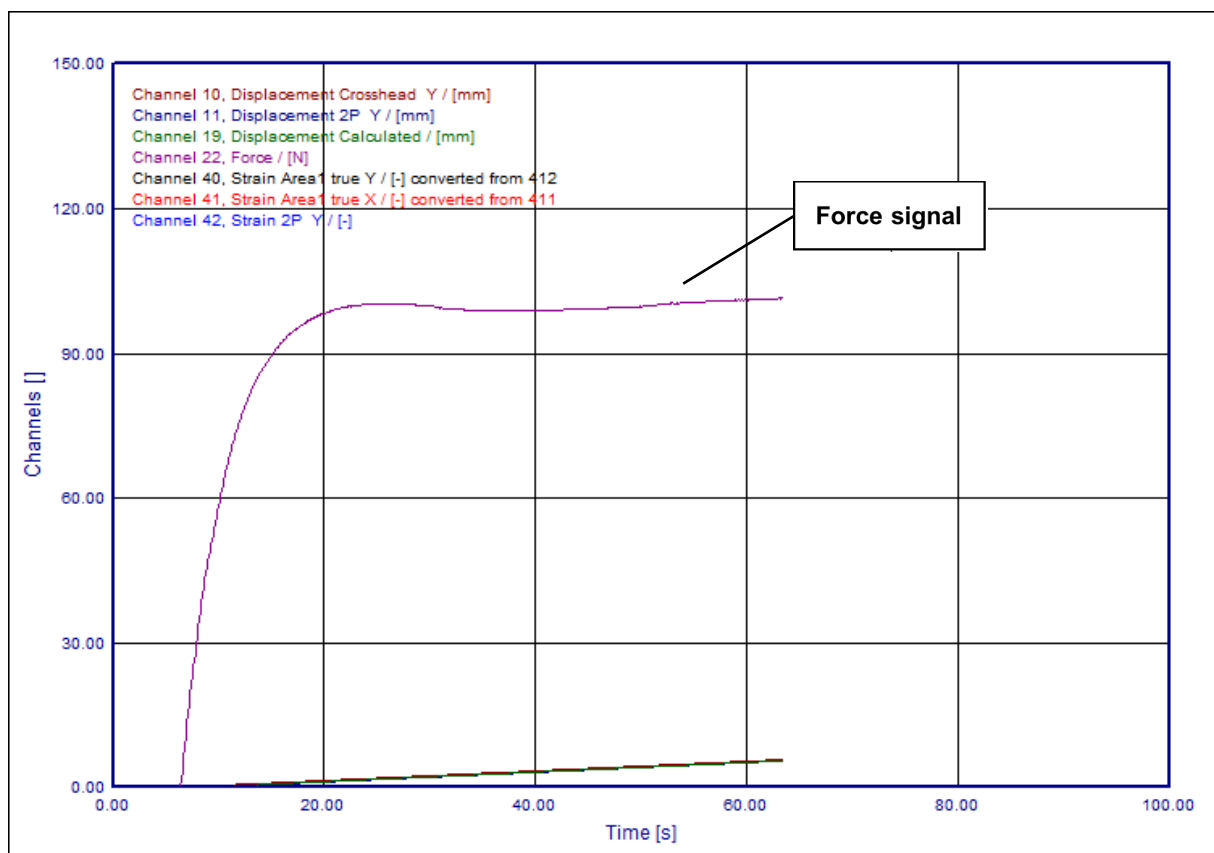


Figure 49:     Example result of a dynamic ST

# 9 Compression test (CT)

## 9.1 Specimen geometry

Following specimens are used for the compression tests:

- IMPETUS-CT-Cube 3x3x2 (Fig.50)
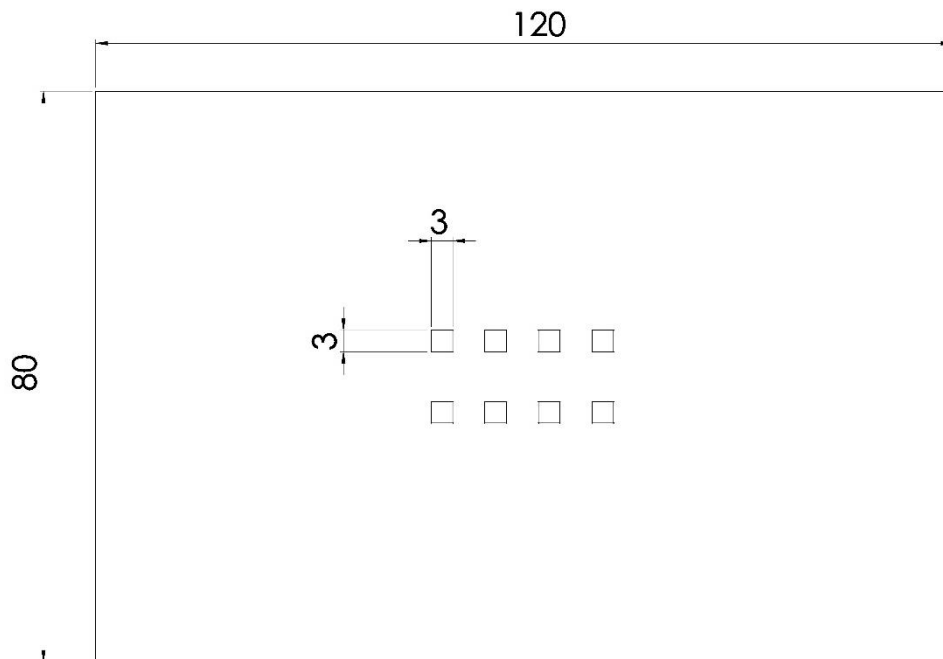- IMPETUS-CT-Celanese 50x10x2 (Fig.51)

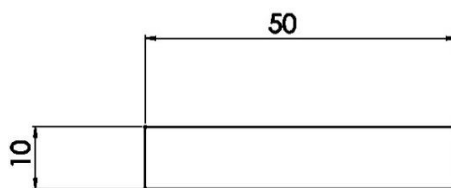Figure 50:     Compression test specimen IMPETUS-CT-Cube, milling pattern

Figure 51:     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 Fig.52.

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 Fig.53. The whole setup is then put into a metal guide for measuring, as depicted in Fig.54.
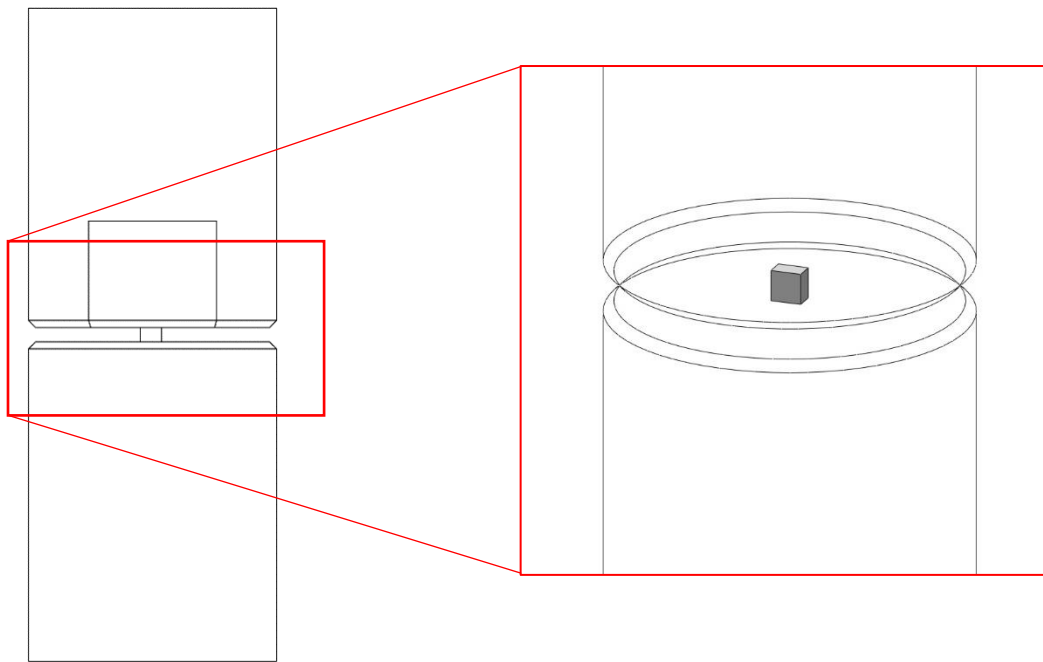
Figure 52:     Static compression test setup, cube specimen



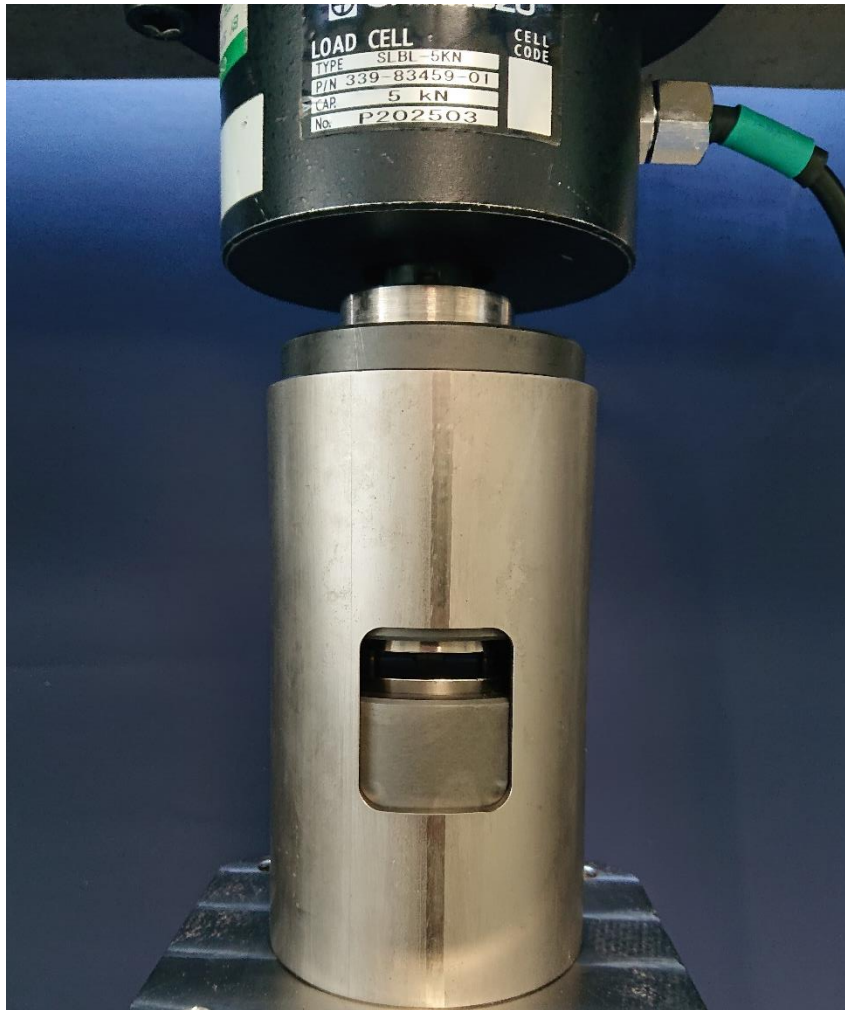Figure 53:     Clamping the Celanese specimen

Figure 54:       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 Tab.6 and Tab.7, relevant specimen measurements are depicted on Fig.55. The strain is calculated using optical DIC, as described for the static TT (6.2.2) and depicted in Fig.57.

Table 6:       Testing parameters static CT – Cube

| 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 7:       Testing parameters static CT – Celanese

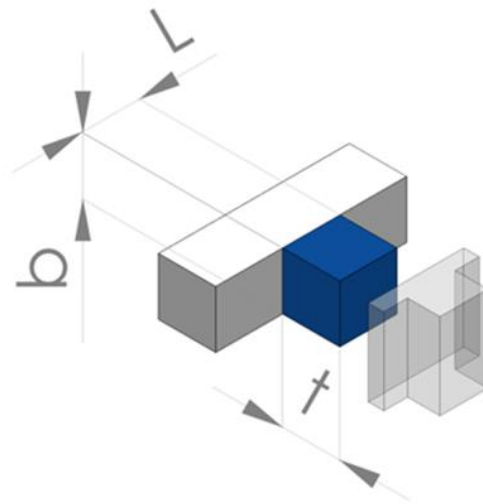| Test-Setup | $v_0$ [m/s] | L [mm] | b [mm] | t [mm] | $\dot{\varepsilon}^*$ [1/s] |
|---|---|---|---|---|---|
| CT_stat (Celanese) | 0.0001 | 10 | 2 | 6 | 0.0167 |

Figure 55:      Relevant specimen measurements for the compression test



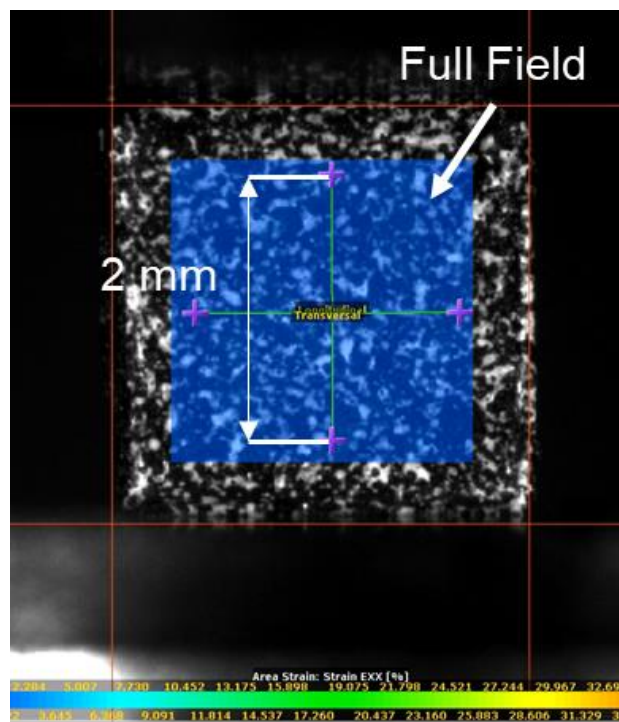Figure 57:      Digital image correlation (DIC) strain measurement CT

## 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 (Fig.3). Its distinct geometry is further highlighted in Fig.58.
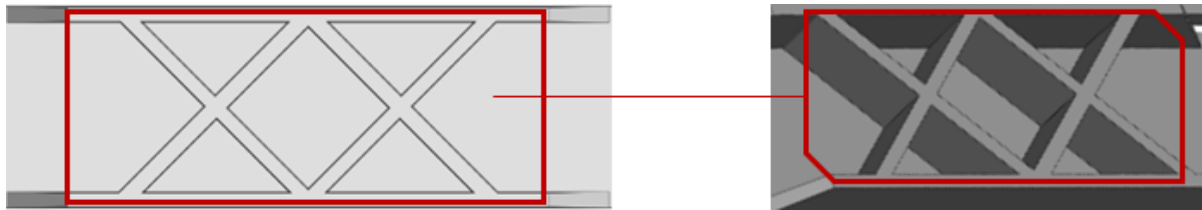


Figure 58:     XX-rib component

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 Fig.59.



Figure 59:     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 Fig.60.
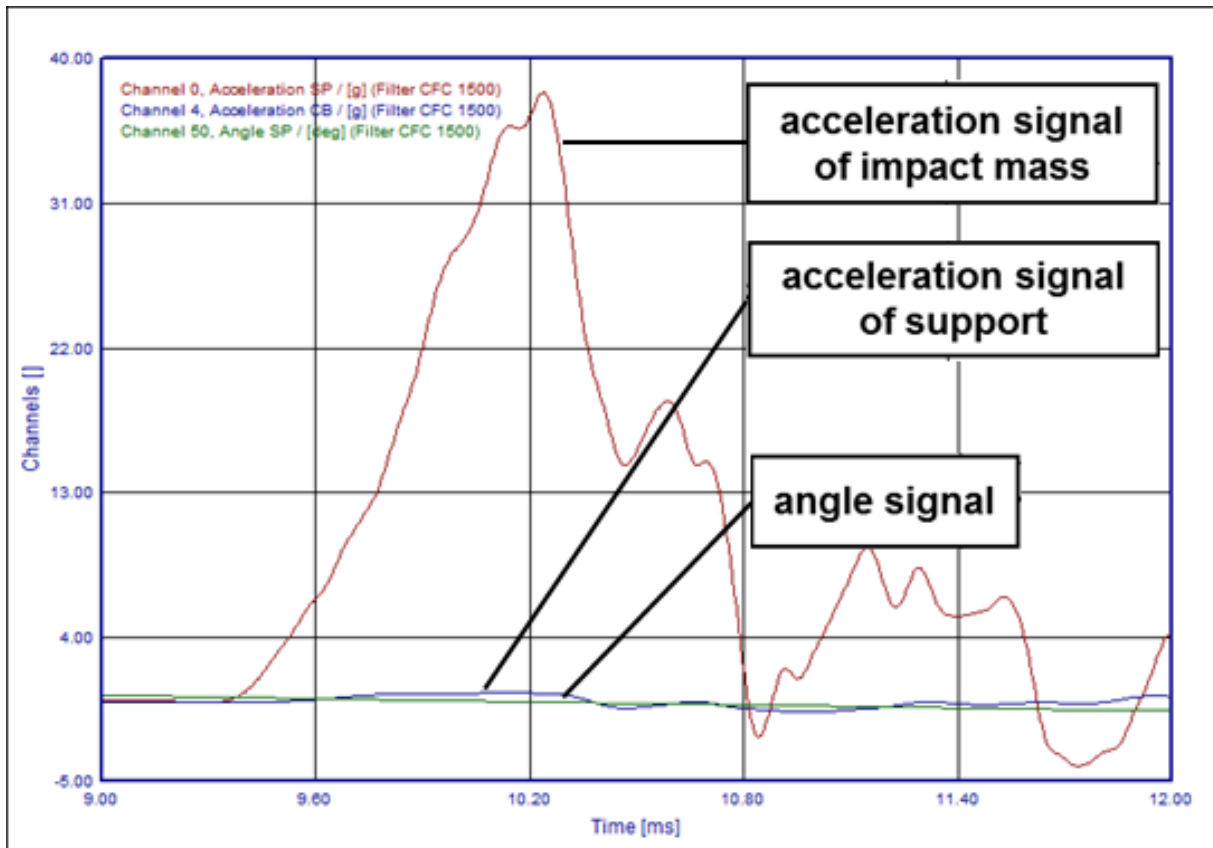
Figure 60:    Example result for acceleration and angle of a XX-Rib component test

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

## 10.2  Dome (COT based on PT)

The Dome component is sawed of the Dome & finger plate (Fig.5). Its distinct geometry is further depicted in Fig.61.
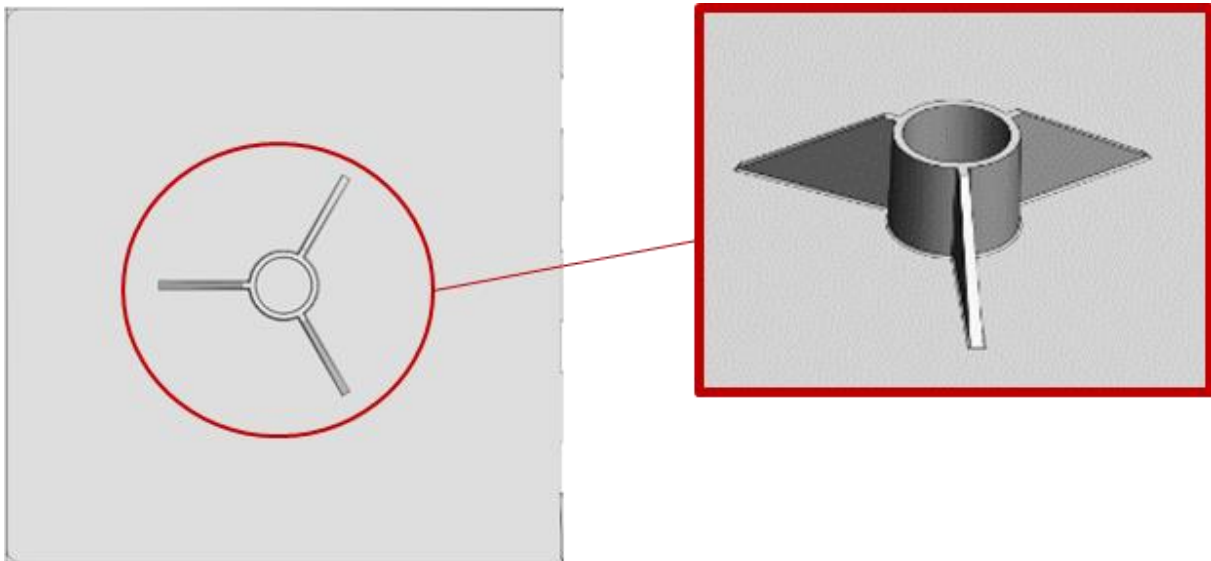


Figure 61:    Dome component

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 Fig.62.
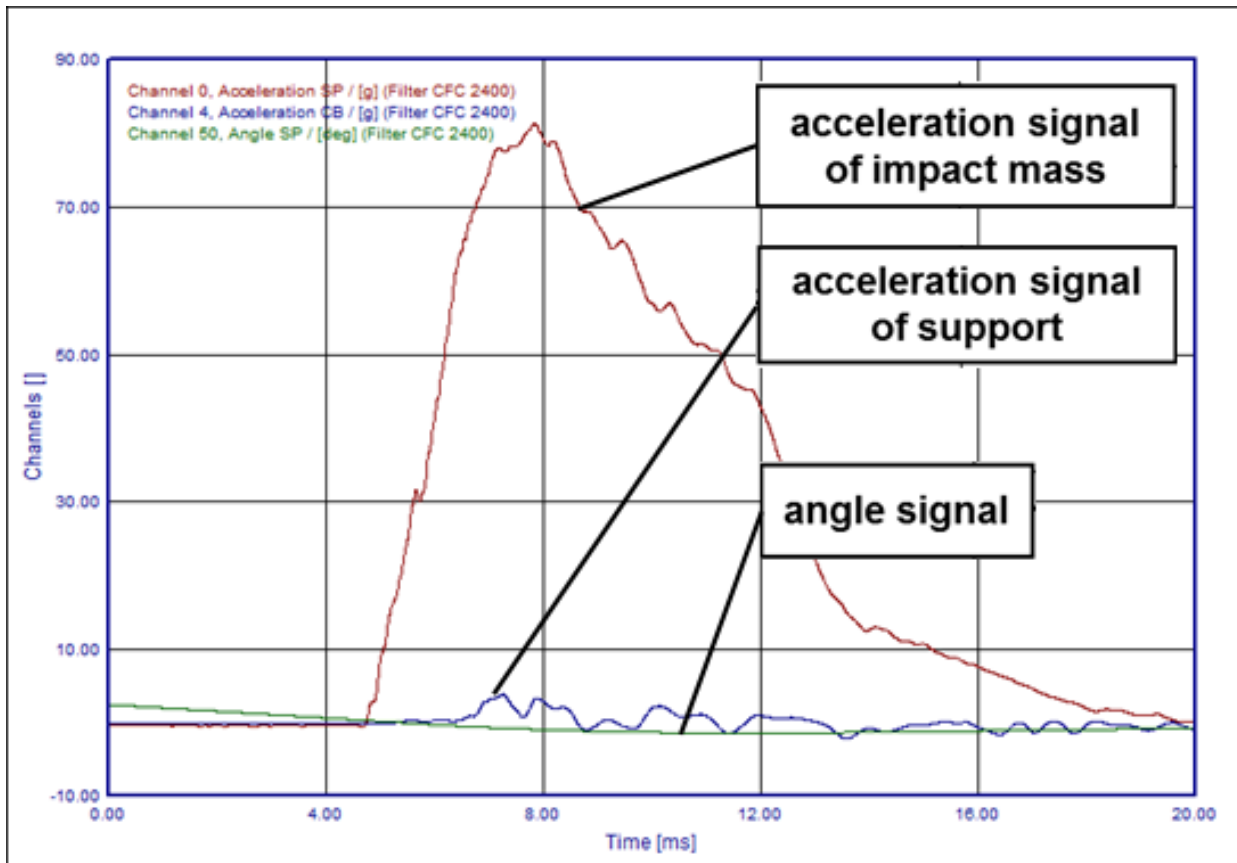
Figure 62:     Example result for acceleration and angle of Dome component test

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

# 11 Appendix

## 11.1 Tolerances

### 11.1.1 Specimen geometries

Specimens are measured in thickness with a digital dial indicator (specified in 11.2), other measurements are taken with a digital calliper (specified in 11.2).

Evaluation relevant measurements are documented individually and tolerated within the range of ±0.05mm, or elsewise discarded. Other measurements, such as total length (3PB, TT, ST, PT, CT-Celanese, CT-Butterfly) and total width (not inner width; TT, PT, ST, CT-Butterfly) are averaged over the first five specimen for each setup and conform to a tolerance of ±1mm.

### 11.1.2 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.

## 11.2 Sensor information

Measuring equipment is checked and calibrated regularly. Tab.8. illustrates calibration intervals, measurement range, resolution and tolerances for sensors and equipment.
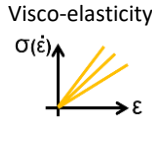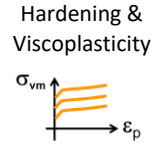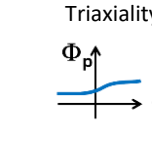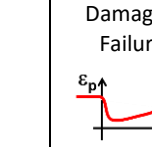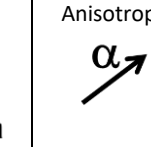
Table 8: Measuring equipment used

| Type | Serial - Nr. | Range | Resolution | Tolerance | Interval [y] |
|---|---|---|---|---|---|
| Calliper | Sylvac S_CalPro IP6736136 | 0 - 150mm | 0.01 mm | ± 0.01 mm | 1 |
| Load cell | Load cell AG-X 500N | ± 500 N | Class 1  1/1000 | ± 1% | 3 |
| Load cell | Load cell AG-X 5kN | ± 5 kN | Class 1  1/500 | ± 1% | 3 |
| Load cell | Load cell AG-X 50kN | ± 50 kN | Class 1  1/1000 | ± 1% | 3 |
| Acceleration sensor | ASC 4211LN-025-OH176D-72047 | ± 25g | 1/100 | ± 1% | 1 |
| Acceleration sensor | ASC 4211LN-050-OAD-72043 | ± 50g | 1/100 | ± 1% | 1 |
| Universal testing machine | Shimadzu AG-X 50kNI3304701042 | 0 - 1060 mm | 0.001 mm | ± 0.1% (0.01 mm s<10 mm) | 3 |
| Testing pendulum | 4a impetus002-BJ06-G3M4 | bis 25 J, 4 m/s und 2 kg | < 2% | ± 1% | 1 |
| Climatic chamber | Memmert HPP 110W413.0062 | 5 - 70 °C10 - 90 % rh | 0.1 °C0.1 % rh | ± 1°C± 2% | 3 |
| Digital dial indicator | Sylvac S_Dial Work BASIC13469420 | 0 - 12.5 mm | 0.001 mm | ± 0.004 mm | 1 |
| Singular weight 50 g | Kern 50 gG1515062 | 50 g | E2± 0.1 mg | ± 0.1 mg | 3 |
| Singular weight 100 g | Kern 100 gG1515063 | 100 g | E2± 0.16 mg | ± 0.2 mg | 3 |
| Singular weight 200 g | Kern 200 gG1515064 | 200 g | E2± 0.3 mg | ± 0.3 mg | 3 |
| Singular weight 1 kg | Kern 1 kgG1515019 | 1000 g | NF1 1.3 mg | ± 0.1 g | 3 |
| Singular weight 5 kg | Kern 5 kgG1515018 | 5000 g | F1± 25.0 mg | ± 0.1 g | 3 |
| Furnace | Memmert UF110plusB415.0375 | 20 - 250 °C | 0.1 °C | ± 1 °C | 3 |
| Scale | sartorius CPA225D-0CE23011313 | 0 - 220 g | 0.0001 g | ± 0.0002 | 3 |
| Digital dial indicator | Sylvac S-Dial Work13269157 | 0-25 mm | 0.01 mm | ± 0.01 mm | 1 |
| Testing pendulum | 4a impetus011-BJ15-G6M6 | bis 50 J, 4 m/s und 3 kg | < 2% | ± 1% | 1 |
| Acceleration sensor | ASC 4211LN-005-0HB7615-17565 | ± 5g | 1/100 | ± 1% | 1 |
| Calliper | Sylvac S_CalONE003888 | 0 - 150mm | 0.01 mm | ± 0.01 mm | 1 |
| Universal testing machine | Shimadzu AGS-X Std 10kNI33065534402 | 0-1000 mm | 0.001 | ± 0.1% (0.01 mm s<10 mm) | 3 |
| Load cell | Load cell AGS-X 500N | ± 500 N | Class 1  1/500 | ± 1% | 3 |
| Acceleration sensor | ASC 4211LN-005-0HB7617-33673 | ± 5g | 1/100 | ± 1% | 1 |
| Acceleration sensor | ASC 4211LN-050-0HB7617-33675 | ± 50g | 1/100 | ± 1% | 1 |
| Acceleration sensor | ASC 4211LN-400-0HB7617-33677 | ± 400g | 1/100 | ± 1% | 1 |
| Testing pendulum | IMPETUS017-BJ18-G7M8 | bis 50 J, 4 m/s und 3 kg | < 2% | ± 1% | 1 |
| Cooling chamber | ARCTIKO/ULUF6021.18 1081016 | -20°C bis -40°C | 0.1°C | ± 2 °C | 3 |
| Furnace | Memmert UF30plusB119.0960 | 20 - 250 °C | 0.1 °C | ± 1 °C | 3 |
| Scalable load cell | HBM 1-CFT/20 kN | 0 - 20 kN | Class 0.5 | 0.1% | 1 |

## 11.3  VALIMAT™ – from test to material card

Depending on the test type different behavior of plastics can be captured (table 1). Base of all material characterization is the 3-point bending test. Using this test at various velocities a simple elastic viscoplastic material card can be modelled. For a more sophisticated material model further tests have to be done. So, the user is able to get all the necessary measurement data for his chosen material model by setting up an appropriate test plan. This leads to the typical characterization pyramid shown in Figure 63.

Table 8: Measurement results in dependence of the test type

| Test type | Visco-elasticity $\sigma(\dot{\varepsilon})$ | Hardening & Viscoplasticity $\sigma_{vm}$ | Triaxiality $\Phi_p$ | Damage / Failure $\varepsilon_p$ | Anisotropy $\alpha$ |
|---|---|---|---|---|---|
| 3-point bending | ✓ | ✓ | | ~ | ✓ |
| Cyclic 3-point bending | | | | ✓ | |
| Clamped 3-point bending | | | ✓ | ✓ | |
| Puncture test | | | | ✓ | |
| Tensile test | | | ✓ | ✓ | |

With the latest version of VALIMAT™, all measurement data (raw data, images, videos, …) are stored in an appropriate structure and can be automatically evaluated (filtering, triggering, calculating further results like energy, strain rate, …) and displayed in VALIMAT:

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).
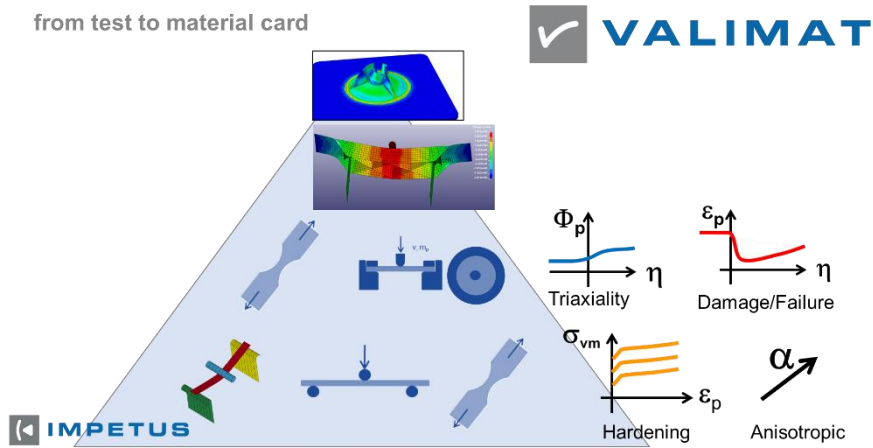


Figure 63:     Characterization pyramid for IMPETUS™; from basic characterization up to final component validation.