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RESEARCH ARTICLE

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Expanded measurement uncertainty concept for the calibration of Charpy pendulum impact machines

Erweitertes Messunsicherheitskonzept bei der Kalibrierung von Charpy-Pendelschlagwerken

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Abstract

With this approach, it is for the first time possible to map all for the direct calibration relevant influences on the impact energy that are to be tested according the standard and to determine complete the respective deviation and measurement uncertainty component. Therefore it is necessary to transfer the tested parameters in influences on the indicated absorbed energy. Based on the numerical example of a presented specific calibration, it has been shown that many influences that have not yet been considered must also be considered, whereas some components can be neglected.

KEYWORDS

Calibration, Charpy, measurement uncertainty, pendulum impact machine, anvil, energy, bias

Abstract

Mit diesem hier vorgestellten Ansatz werden erstmalig alle für die direkte Kalibrierung relevanten in der Norm abzuprüfenden Einflüsse auf die Auswirkung der Schlagenergie abgebildet und vollständig die jeweilige Abweichung und Messunsicherheitskomponente ermittelt. Hierzu ist es notwendig, die geprüften Parameter in Einflüsse auf die angezeigte verbrauchte Schlagenergie zu übertragen. Anhand eines vorgestellten Zahlenbeispiels einer konkreten Kalibrierung hat sich gezeigt, dass viele bislang noch nicht betrachteten Einflüsse zusätzlich zu berücksichtigen sind, einige Komponenten aber auch vernachlässigt werden können.

SCHLÜSSELWÖRTER

Kalibrierung, Messunsicherheit, Pendelschlagwerk, Widerlager, Schlagenergie, Abweichung

1 | INTRODUCTION

If characteristic values are determined in mechanical-technological tests, they must be reliable, resilient and comparable on different testing machines [1, 2]. Therefore, it is essential to calibrate testing machines such as Charpy pendulum impact machines.

The calibration is regulated by the EN ISO 148-2:2016 standard [3]. A distinction is made between direct and indirect calibration. The direct calibration involves measuring individual quantities such as forces and angles. The indirect method uses reference test pieces to verify points on the measuring scale for absorbed energy.

The problem of the direct method is, that it sometimes leads to significantly different impact values when testing test pieces of the same material on two different machines that had been evaluated by the direct method and met all requirements. Therefore an additional indirect calibration with reference test pieces is required. The ISO 148-2 requires that the pendulum impact machine must met the requirements of both methods [3, page v].

However, the standard allows many reductions in the scope of calibration for direct calibration (limited direct verification). Based on the many years of experience of calibration laboratories, the DIN Working Committee recommends always performing the complete direct verification [4 chapter National Foreword]. This allows a greater reliability regarding the accuracy of the impact energy and comparability [5].

Because direct calibration can still lead to unreliable results, it is essential to research this more closely.

To obtain reliable results, it is essential to consider measurement uncertainties. For many years, the calculation of measurement uncertainties for the calibration of pendulum impact machines has been studied [5–7]. Due to the complexity of the direct calibration, no comprehensive approach has yet been developed.

So far, ISO 148-2 only takes the following quantities into account [3 Appendix B]:

- Bias due to the energy calculation from measured angles (in energy units),
- Bias due to the impact velocity, however, this influence is neglected,
- Bias due to in the difference between pendulum length and centre of percussion,however, no reference is made to the impact on energy,
- Bias in the energy read from an analogue or digital scale (in energy units).

However, direct calibration requires a multitude of quantities to be determined. This publication presents a comprehensive measurement uncertainty analysis for all essential parameters of direct calibration:

- Deviation of potential energy,
- Force measuring method for potential energy,
- Positioning of force-proving instrument for potential energy,
- Horizontal alignment of the pendulum for potential energy,
- Absorbed energy,
- Horizontal reference plane,
- Horizontal alignment without a reference plane,
- Hanging free pendulum,
- Contact between striker and test piece,
- Indicating equipment,
- Loss due to friction of indicating pointer,
- Losses caused by bearing friction and air resistance,
- Distance to the centre of percussion from the axis of rotation,
- Radius of striking edge,
- Angle of striker,
- Line of contact of the striker perpendicular to test piece,
- Parallel test piece supports without offset,
- Axis of the test piece parallel to the axis of rotation,
- Parallel anvils without offset,
- Angle between anvil and test piece supports,
- Distance between anvils,
- Striker needs to pass the anvil in the middle,
- Axial play in the pendulum bearings,
- Radial play in the pendulum bearings,
- Radius of anvils.

2 | CALCULATION OF THE MEASUREMENT UNCERTAINTY

For uncorrelated input quantities the square of the standard uncertainty associated with the output estimate y is given by [8, 9]

$$u^2_{\mathrm{K\,direct}}(y) = \sum_{i=1}^{N} u^2_{\mathrm{i}}(y) \tag{1}$$

The expanded uncertainty of measurement U, obtained by multiplying the standard uncertainty $u(y)$ of the output estimate y by a coverage factor k, will be calculated according

$$U = k \cdot u(y) \tag{2}$$

in our case with the standard coverage factor $k = 2$

$$U_{\mathrm{K\,direct}} = 2 \cdot u_{\mathrm{K\,direct}} \tag{3}$$

To specify this total measurement uncertainty, the effects on the error of all parameters under investigation must be expressed in energy units.

For this purpose

- calculations,
- empirical experiments, and
- finite element simulations

were carried out.

If the effect can be determined directly, e.g. in the case of the deviation of the potential energy, these can be calculated by mathematical models, see formula (5).

However, many influences cannot be described physically or mathematically. For this purpose, empirical tests were conducted in this study and considered as numerical equations. These were mostly carried out on a high-precision reference pendulum impact machine[1] using certified reference samples and thus provide a good initial estimate. For this purpose, changes or manipulations are made on the reference pendulum and the changes compared to the ideal state depending on the extent of the change made. However, it should be noted that these results are only rough approximations, as they were determined using only a finite number of certified reference specimens and predominantly on a single impact tester. This does not necessarily apply to all pendulum impact machines and cannot be extended without restriction to other energy levels. It may be useful to determine these influences under different boundary conditions through further tests and thus optimize them.

Some influences are also based on results of finite element simulations (e.g. influence of the striking edge) or were investigated by variations of measurement method (e.g. force measurement methods).

These determined numerical value equations are then considered as measurement uncertainty component as a rectangular distribution in the form:

$$u_c = \frac{1}{\sqrt{3}} \cdot K_{\text{empirical}} \tag{4}$$

3 | UNCERTAINTY COMPONENTS

The derivation of the components is discussed below. Some of them will be calculated based on physical relationships, some are determined by measuring influencing factors and some of them are determined from tests with reference test pieces.

The combined standard uncertainty of physical relationships is calculated under the assumption that the input variables are uncorrelated, according to *equation* (5)

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i) \tag{5}$$

The required uncertainty components, e.g. from multiple measurements or from the measurement uncertainty of the standards, are not explicitly listed below, but are generally determined as follows [9]:

Experimental standard deviation $s(q)$ of the arithmetic mean

$$s(q) = \sqrt{\frac{1}{n-1} \cdot \left[\sum_{j=1}^{n} (q_j - \overline{q})^2\right]} \tag{6}$$

with n as the number of observed values and q the values and the arithmetic mean $\overline{q}$.

Assuming a rectangular probability distribution with upper limit a and lower limit $-a$, the measurement uncertainty is estimated:

$$u^2(x_i) = \frac{1}{3} \cdot a^2(y) \tag{7}$$

where the difference between the upper and the lower limit $2a$ is [9, chapter 3.3.2 c].

The considered quantities are shown in the Ishikawa diagram and are described in the following chapter, *Figure 1*.

Formula symbols used

a	Upper limit a and lower limit $-a$ of a single measured value for the estimation of a rectangular probability distribution
$a_{\text{increment standard}}$	Increment of the standard e.g. from the available gauges when using a gauges
$a_{\text{measuring angle}}$	Value a of reproducibility of using the angle meter
$A_{\text{measuring method}}$	Relative deviation of different measuring methods
a_{Pos}	Estimated accuracy of positioning of force-proving instrument
$a_{\text{reaction time}}$	Reaction time when using the stopwatch
$a_{\text{resolution standard}}$	Resolution of the used standard
$a_{\text{scale standard}}$	Scale of the used standard e.g. of the scale of angle meter
F	Force exerted by the pendulum when measured at a distance l_2
$F_{\text{delta F}}$	Deviation of the force due to an inclination of $x/1000$ for imperfect horizontal alignment of the pendulum
g	Acceleration due to gravity
k	Coverage factor
K_1	Indicated absorbed energy of a test without a test piece in position with indicating pointer
K_2	Indicated absorbed energy of a test without a test piece in position without indicating pointer

K_3	Indicated absorbed energy after 11 half swings when the machine is operated in the normal manner without a test piece in position and without resetting the indication mechanism
K_{calc}	Calculated energy
$K_{empirical}$	Deviations due to empirically determined quantities
K_N	Nominal initial potential energy
K_P	Potential energy
K_S	Indicated absorbed energy
l	Distance to the point of application of the force F from the axis of rotation
l_1	Distance to the centre of percussion from the axis of rotation
l_2	Distance to the point of application of the force F from the axis of rotation
$l_{distance\ anvils}$	Distance between anvils
L_i	Measured distances to determine l_2, see
p'	Absorbed energy loss caused by bearing friction and air resistance
r	Resolution of the pendulum scale
r_{anvil}	Radius of anvil
$s_{bearing}$	Half distance between the two bearings, see
$s_{hanging\ free\ pendulum}$	Deviation of the position of the free hanging pendulum
$s_{offset\ anvil}$	Offset of the anvils
$s_{radial\ play}$	Inclined position of the striker because of $\alpha_{radial\ play}$
t	Period of the pendulum
U	Expanded uncertainty of measurement
$u_{deviation\ standard}$	Deviation of the used standard e.g. of calliper according calibration certificate
$u_{K\ direct}$	Combined standard uncertainty for the direct calibration with influences on the indicated energy
$U_{K\ direct}$	Expanded uncertainty for the direct calibration with influences on the indicated energy
$u_{standard}$	Measurement uncertainty of the calibration of the standard e.g. stopwatch, calliper, ...
u_t	Measurement uncertainty of the time measurement
α	Angle of fall of the pendulum
α_{axis}	Inclined position of a imperfect axis of the test piece parallel to the axis of rotation
$\alpha_{contact\ striker}$	Inclination of the striker for contact between striker and test piece
$\alpha_{delta\ F}$	Inclined position responsible for $F_{delta\ F}$
$\alpha_{delta\ Ref}$	Inclined position of a imperfect horizontal reference plane
$\alpha_{line\ of\ contact}$	Angle of the turned striker of a imperfect line of contact of the striker perpendicular to test piece
$\alpha_{radial\ play}$	Inclined angle of the pendulum axis or of the pendulum rod and thus of the striker caused by radial play
β	Angle of rise of the pendulum
$\Delta r_{striker}$	Deviation to the nominal radius 2 mm of striking edge

Further symbols are given in chapters 4.1 and 4.2 for their clear assignment to the combined instrument bias and the combined standard uncertainty.

3.1 | Potential energy

3.1.1 | Deviation of potential energy

To evaluate the real potential energy, it is necessary to measure the pendulum length. Because it cannot be measured directly, it will be determined usually from 3 measurements, *Figure 2*.

$$l_2 = l = L_1 - \frac{L_2}{2} - \frac{L_3}{2} \tag{8}$$

For the calculation of the deviation of the potential energy A, the following measurement equation is valid:

$$A = F \cdot \left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot (1 - \cos\alpha) - K_N \tag{9}$$

F is the force exerted by the pendulum, α is the angle of fall and K_N is the nominal initial potential energy.

The uncertainty will be calculated according

$$\begin{aligned} u_A^2(y) = \sum_{i=1}^{6}\left(\frac{\partial A}{\partial x_i}\right)^2 \cdot u^2(x_i) = \left(\frac{\partial A}{\partial F}\right)^2 \cdot (s^2(\overline{F}) \\ + u^2(F)) + \left(\frac{\partial A}{\partial L_1}\right)^2 \cdot (s^2(\overline{L_1}) + u^2(L_1)) \\ + \left(\frac{\partial A}{\partial L_2}\right)^2 \cdot (s^2(\overline{L_2}) + u^2(L_2)) \\ + \left(\frac{\partial A}{\partial L_3}\right)^2 \cdot (s^2(\overline{L_3}) + u^2(L_3)) \\ + \left(\frac{\partial A}{\partial \alpha}\right)^2 \cdot (s^2(\overline{\alpha}) + u^2(\alpha)) \\ + \left(\frac{\partial A}{\partial K_N}\right)^2 \cdot (s^2(K_N)) \end{aligned} \tag{10}$$

or respectively according

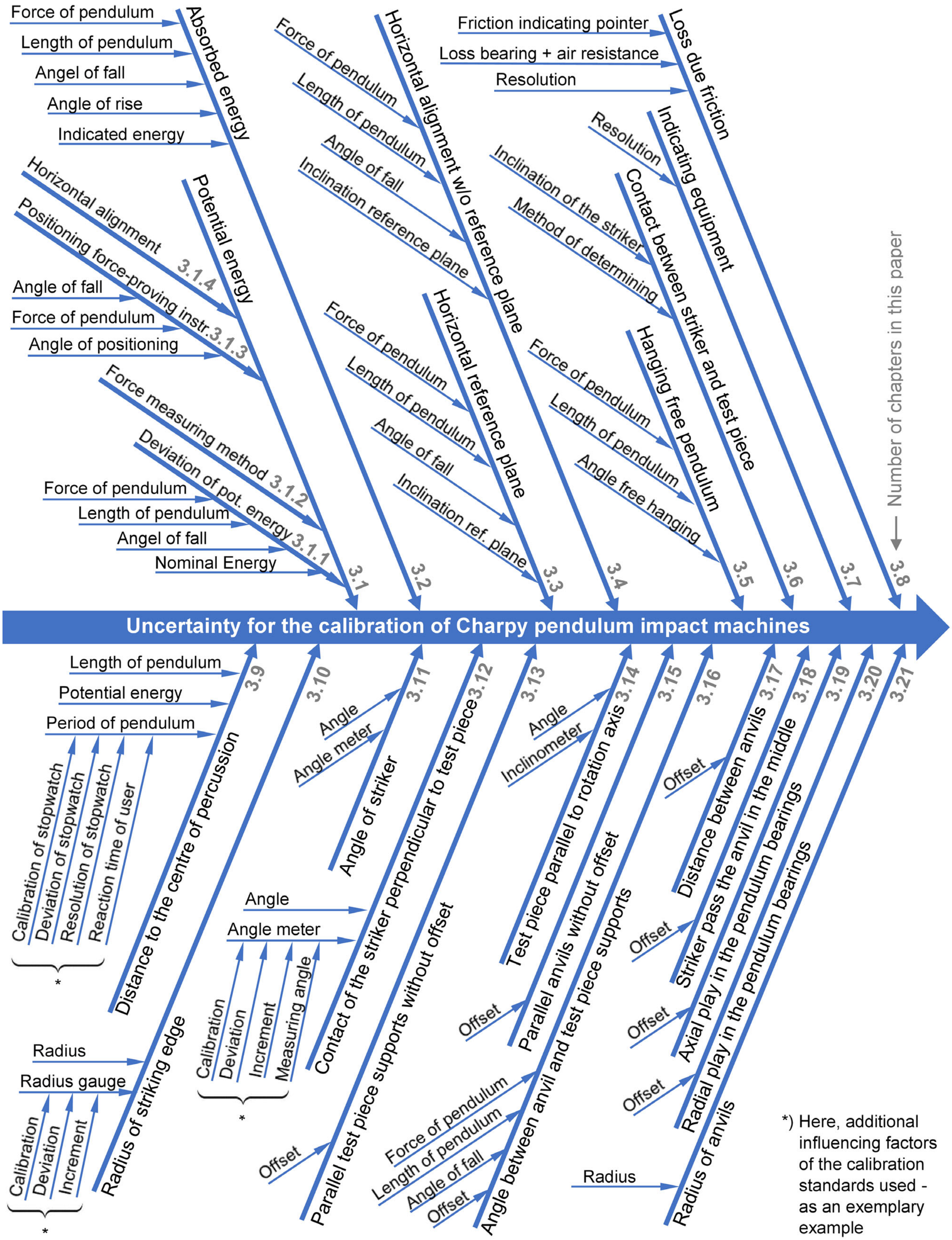

FIGURE 1 Ishikawa diagram of the considered quantities to calculate the uncertainty.

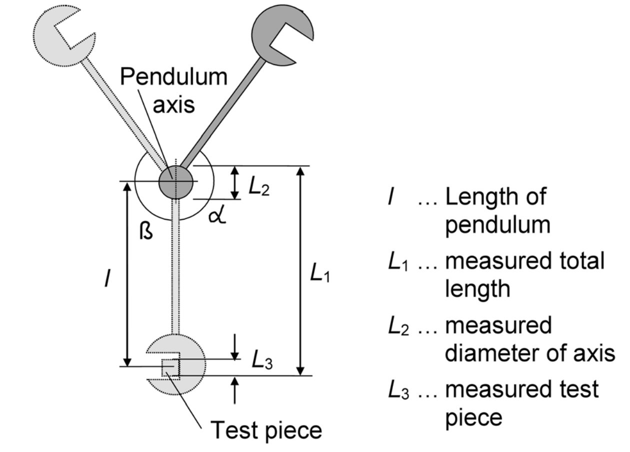

FIGURE 2 Measuring of the pendulum length.

$$\begin{aligned} u_A^2(y) &= \sum_{i=1}^{N}\left(\frac{\partial A}{\partial x_i}\right)^2 \cdot u^2(x_i) \\ &= \left(\left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right)\cdot(1-\cos\alpha)\right)^2 \cdot \left(s^2(\overline{F}) + u^2(F)\right) \\ &\quad + (F\cdot(1-\cos\alpha))^2 \cdot \left(s^2(\overline{L_1}) + u^2(L_1)\right) \\ &\quad + \left(\frac{-1}{2}F\cdot(1-\cos\alpha)\right)^2 \cdot \left(s^2(\overline{L_2}) + u^2(L_2)\right) \\ &\quad + \left(\frac{-1}{2}F\cdot(1-\cos\alpha)\right)^2 \cdot \left(s^2(\overline{L_3}) + u^2(L_3)\right) \\ &\quad + \left(F\cdot\left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right)\cdot\sin\alpha\right)^2 \cdot \left(s^2(\overline{\alpha}) + u^2(\alpha)\right) \\ &\quad + (-1)^2 \cdot (s^2(K_N)) \end{aligned} \tag{11}$$

It should be noted that the measurement uncertainty of the force-proving instrument $u(F)$ must be determined based on the measurement uncertainty for on-site use. ISO 376 provides in chapter C.1.1 specific information on this [10]. $s(K_N)$ is assumed to be zero, because it is the nominal value of the pendulum impact machine.

In order to take all measurement uncertainty components for the measurement of the force into account, further influencing parameters must be considered as described in the following chapters 3.1.2 to 3.1.4.

3.1.2 | Force measuring method

To measure the pendulum's weight, the point of impact of the center of test piece is transferred with a marking to the striker when the pendulum is suspended vertically. The pendulum's weight can then be determined at this marked point when the pendulum is horizontally aligned. The method used to determine this weight has a decisive influence on the measurement uncertainty; see method a) to c), *Figure 3*.

Method a) is the most common and easiest, method b) with an extremely short stilt for application of forces provides the smallest measurement uncertainty, however, a correspondingly small force measuring device is necessary to get close to the striker and method c) also has a small measurement uncertainty but is actually too complex to implement.

Depending on the force measuring method[2] and the length of the stilt for application of forces, there occur lateral

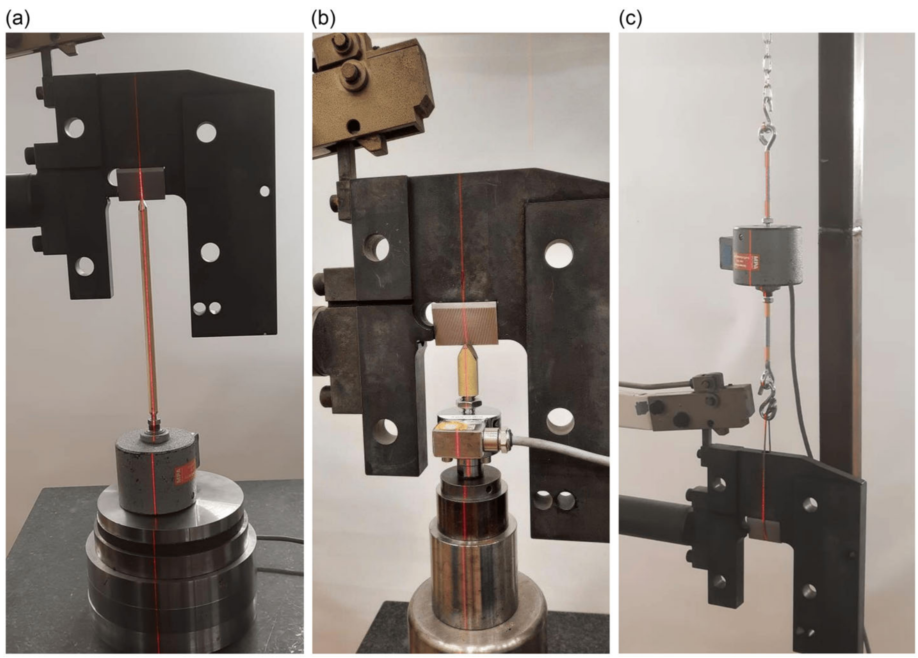

FIGURE 3 Calibration setup for determining the weight of the pendulum, method a)-c).

forces which generates different deviations from the actual force. As realistic values (empirical estimates based on 10 measurements with laser alignment), the following values can be used for measuring methods a) to c) (with a maximum inclined position for application of forces of 0.25°):

occurred bias method a) $A_{\text{measuring method}} = 0.7\ \%$
method b) $A_{\text{measuring method}} = 0.07\ \%$
method c) $A_{\text{measuring method}} = 0.15\ \%$

The error due to the force measuring method $K_{\text{P measuring method}}$ is therefore:

$$K_{\text{P measuring method}} = A_{\text{measuring method}} \cdot K_{\text{P}} \tag{12}$$

K_{P} is the potential energy.

Due to the measuring method, very large errors can occur here. These depend on your own method and equipment.

3.1.3 | Positioning of force-proving instrument

The point of impact is transferred from the center of the test piece to the striker. The force-proving instrument will be positioned at this mark under the horizontally aligned pendulum. The accuracy of this positioning a_{Pos} is about (0.5 … 1.0) mm.

The following applies to potential energy:

$$K_{\text{P Pos}} = F \cdot a_{\text{Pos}} \cdot (1 - \cos\alpha) \tag{13}$$

The uncertainty will be calculated according

$$\begin{aligned} u^2_{\text{KP Pos}}(y) &= \sum_{i=1}^{3} \left(\frac{\partial K_{\text{P Pos}}}{\partial x_{\text{i}}}\right)^2 \cdot u^2(x_{\text{i}}) \\ &= \left(\frac{\partial K_{\text{P Pos}}}{\partial F}\right)^2 \cdot (s^2(\overline{F}) + u^2(F)) \\ &\quad + \left(\frac{\partial K_{\text{P Pos}}}{\partial a_{\text{Pos}}}\right)^2 \cdot (s^2(\overline{a}_{\text{Pos}})) \\ &\quad + \left(\frac{\partial K_{\text{P Pos}}}{\partial \alpha}\right)^2 \cdot (s^2(\overline{\alpha}) + u^2(\alpha)) \end{aligned} \tag{14}$$

or respectively according

$$\begin{aligned} u^2_{\text{KP Pos}}(y) &= \sum_{i=1}^{3} \left(\frac{\partial K_{\text{P Pos}}}{\partial x_{\text{i}}}\right)^2 \cdot u^2(x_{\text{i}}) \\ &= (a_{\text{Pos}} \cdot (1 - \cos\alpha))^2 \cdot (s^2(\overline{F}) + u^2(F)) \\ &\quad + (F \cdot (1 - \cos\alpha))^2 \cdot u^2(a_{\text{Pos}}) \\ &\quad + (F \cdot a_{\text{Pos}} \cdot \sin\alpha)^2 \cdot (s^2(\overline{\alpha}) + u^2(\alpha)) \end{aligned} \tag{15}$$

and for $u(a_{\text{Pos}})$

$$u_{\text{Pos}} = \frac{1}{\sqrt{3}} \cdot a_{\text{Pos}} \tag{16}$$

3.1.4 | Horizontal alignment of the pendulum

According to ISO 148-2, the pendulum must be aligned horizontally to at least 15/1000 [3, chapter 6.4.2], *Figure 4*.

For the deviation due to an inclination of $x/1000$, the following applies:

$$F_{\text{delta F}} = F \cdot (1 - \cos\alpha_{\text{delta F}}) \tag{17}$$

and also, for the energy

$$K_{\text{P delta F}} = F \cdot l_2 \cdot (1 - \cos\alpha_{\text{delta F}}) \tag{18}$$

combined with

$$\alpha_{\text{delta F}} = \arctan(x/1000) \tag{19}$$

The uncertainty is given by:

$$\begin{aligned} u^2_{\text{KP delta F}}(y) &= \sum_{i=1}^{5} \left(\frac{\partial K_{\text{P delta F}}}{\partial x_{\text{i}}}\right)^2 \cdot u^2(x_{\text{i}}) \\ &= \left(\frac{\partial K_{\text{P Ref}}}{\partial F}\right)^2 \cdot (s^2(\overline{F}) + u^2(F)) \\ &\quad + \left(\frac{\partial K_{\text{P Ref}}}{\partial L_1}\right)^2 \cdot (s^2(\overline{L_1}) + u^2(L_1)) \\ &\quad + \left(\frac{\partial K_{\text{P Ref}}}{\partial L_2}\right)^2 \cdot (s^2(\overline{L_2}) + u^2(L_2)) \\ &\quad + \left(\frac{\partial K_{\text{P Ref}}}{\partial L_3}\right)^2 \cdot (s^2(\overline{L_3}) + u^2(L_3)) \\ &\quad + \left(\frac{\partial K_{\text{P Ref}}}{\partial \alpha_{\text{delta F}}}\right)^2 \cdot (s^2(\overline{\alpha}_{\text{delta F}})) \end{aligned} \tag{20}$$

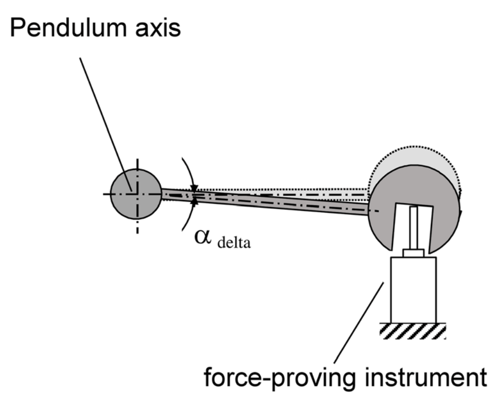

FIGURE 4 Horizontal alignment of the pendulum for measurement of force.

The partial derivative gives

$$
\begin{aligned}
u^2_{\mathrm{KP\,delta\,F}}(y) &= \sum_{i=1}^{5}\left(\frac{\partial K_{\mathrm{P\,delta\,F}}}{\partial x_{\mathrm{i}}}\right)^2 \cdot u^2(x_{\mathrm{i}}) \\
&= \left(\left(L_1-\frac{L_2}{2}-\frac{L_3}{2}\right)\cdot(1-cos\alpha_{\mathrm{delta\,F}})\right)^2 \\
&\quad \cdot (s^2(\overline{F})+u^2(F)) \\
&\quad + (F\cdot(1-cos\alpha_{\mathrm{delta\,F}}))^2\cdot(s^2(\overline{L_1})+u^2(L_1)) \\
&\quad + \left(\frac{-1}{2}F\cdot(1-cos\alpha_{\mathrm{delta\,F}})\right)^2\cdot(s^2(\overline{L_2})+u^2(L_2)) \\
&\quad + \left(\frac{-1}{2}F\cdot(1-cos\alpha_{\mathrm{delta\,F}})\right)^2\cdot(s^2(\overline{L_3})+u^2(L_3)) \\
&\quad + \left(F\cdot\left(L_1-\frac{L_2}{2}-\frac{L_3}{2}\right)\cdot sin\alpha_{\mathrm{delta\,F}}\right)^2 \\
&\quad \cdot (u^2_{\mathrm{delta\,F}}+u^2(\alpha_{\mathrm{delta\,F}}))
\end{aligned}
\tag{21}
$$

3.2 | Absorbed energy

The error of the indicated absorbed energy $K_{\text{error indicated energy}}$ is

$$
\begin{aligned}
K_{\text{error indicated energy}} &= K_{\mathrm{calk}} - K_{\mathrm{S}} \\
&= F\cdot\left(L_1-\frac{L_2}{2}-\frac{L_3}{2}\right)\cdot(cos\beta-cos\alpha)-K_{\mathrm{S}}
\end{aligned}
\tag{22}
$$

K_{calc} is the calculated energy, K_{S} is the indicated absorbed energy and β is the angle of rise of the pendulum.

The standard uncertainty is given by

$$
\begin{aligned}
&u^2_{\text{K error indicated energy}}(y) \\
&= \sum_{i=1}^{7}\left(\frac{\partial K_{\text{error indicated energy}}}{\partial x_{\mathrm{i}}}\right)^2\cdot u^2(x_{\mathrm{i}}) \\
&= \left(\frac{\partial K_{\text{error indicated energy}}}{\partial F}\right)^2\cdot(s^2(\overline{F})+u^2(F)) \\
&\quad + \left(\frac{\partial K_{\text{error indicated energy}}}{\partial L_1}\right)^2\cdot(s^2(\overline{L_1})+u^2(L_1)) \\
&\quad + \left(\frac{\partial K_{\text{error indicated energy}}}{\partial L_2}\right)^2\cdot(s^2(\overline{L_2})+u^2(L_2)) \\
&\quad + \left(\frac{\partial K_{\text{error indicated energy}}}{\partial L_3}\right)^2\cdot(s^2(\overline{L_3})+u^2(L_3)) \\
&\quad + \left(\frac{\partial K_{\text{error indicated energy}}}{\partial \alpha}\right)^2\cdot(s^2(\overline{\alpha})+u^2(\alpha)) \\
&\quad + \left(\frac{\partial K_{\text{error indicated energy}}}{\partial \beta}\right)^2\cdot(s^2((\overline{\beta})+u^2(\beta)) \\
&\quad + \left(\frac{\partial K_{\text{error indicated energy}}}{\partial K_S}\right)^2\cdot(s^2(K_{\mathrm{S}}))
\end{aligned}
\tag{23}
$$

and the result is

$$
\begin{aligned}
&u^2_{\text{K error indicated energy}}(y) \\
&= \sum_{i=1}^{7}\left(\frac{\partial K_{\text{error indicated energy}}}{\partial x_{\mathrm{i}}}\right)^2\cdot u^2(x_{\mathrm{i}}) \\
&= \left(\left(L_1-\frac{L_2}{2}-\frac{L_3}{2}\right)\cdot(cos\,\beta-cos\,\alpha)\right)^2 \\
&\quad \cdot(s^2(\overline{F})+u^2(F)) \\
&\quad + (F\cdot(cos\,\beta-cos\,\alpha))^2\cdot(s^2(\overline{L_1})+u^2(L_1)) \\
&\quad + \left(F\cdot\left(\frac{-1}{2}\right)\cdot(cos\,\beta-cos\,\alpha)\right)^2 \\
&\quad \cdot(s^2(\overline{L_2})+u^2(L_2)) \\
&\quad + \left(F\cdot\left(\frac{-1}{2}\right)\cdot(cos\,\beta-cos\,\alpha)\right)^2\cdot(s^2(\overline{L_3})+u^2(L_3)) \\
&\quad + \left(F\cdot\left(L_1-\frac{L_2}{2}-\frac{L_3}{2}\right)\cdot(-sin\,\beta)\right)^2 \\
&\quad \cdot(s^2(\overline{\alpha})+u^2(\alpha)) \\
&\quad + \left(F\cdot\left(L_1-\frac{L_2}{2}-\frac{L_3}{2}\right)\cdot(sin\,\alpha)\right)^2\cdot(s^2(\overline{\beta})+u^2(\beta)) \\
&\quad + (-1)^2\cdot(u^2_{\mathrm{r}}(K_{\mathrm{S}}))
\end{aligned}
\tag{24}
$$

u_{r} is the standard uncertainty of the resolution of the pendulum scale.

3.3 | Horizontal reference plane

According the standard the machine shall be installed so that the reference plane is horizontal to within 2/1000 [3, chapter 6.3.3]. This has an influence on the input of the energy, *Figure 5*. In case of an inclination the original position 1 becomes then, for example, position 2.

The inclination by $x/1000$ results in a change of the angle of fall $\alpha_{\mathrm{delta\,Ref}}$ to

$$
\alpha_{\mathrm{delta\,Ref}} = arctan(x/1000) \tag{25}
$$

The change in the angle of fall is to be considered negative if the energy decreases due to the inclination (i.e. the pendulum moves downwards from the initial position), and it is positive if the energy increases.

The error of the applied energy $K_{\mathrm{P\ Ref}}$ due to the non-horizontal reference surface is

$$
K_{\mathrm{P\,Ref}} = F\cdot\left(L_1-\frac{L_2}{2}-\frac{L_3}{2}\right)\cdot(cos\,\alpha-cos(\alpha+\alpha_{\mathrm{delta\,Ref}})) \tag{26}
$$

The standard deviation is given by

$$\begin{aligned}
u^2_{\mathrm{KP\,Ref}}(y) &= \sum_{i=1}^{6}\left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial x_{\mathrm{i}}}\right)^2 \cdot u^2(x_{\mathrm{i}}) \\
&= \left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial F}\right)^2 \cdot (s^2(\overline{F}) + u^2(F)) \\
&\quad + \left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial L_1}\right)^2 \cdot (s^2(\overline{L_1}) + u^2(L_1)) \\
&\quad + \left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial L_2}\right)^2 \cdot (s^2(\overline{L_2}) + u^2(L_2)) \\
&\quad + \left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial L_3}\right)^2 \cdot (s^2(\overline{L_3}) + u^2(L_3)) \\
&\quad + \left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial \alpha}\right)^2 \cdot (s^2(\overline{\alpha}) + u^2(\alpha)) \\
&\quad + \left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial \alpha_{\mathrm{delta\,Ref}}}\right)^2 \cdot (s^2(\overline{\alpha}_{\mathrm{delta\,Ref}}) \\
&\quad + u^2(\alpha_{\mathrm{delta\,Ref}}))
\end{aligned} \tag{27}$$

The partial derivative is given by

$$\begin{aligned}
u^2_{\mathrm{KP\,Ref}}(y) &= \sum_{i=1}^{6}\left(\frac{\partial K_{\mathrm{P\,Ref}}}{\partial x_{\mathrm{i}}}\right)^2 \cdot u^2(x_{\mathrm{i}}) \\
&= \left(\left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot (1 - cos(\alpha + \alpha_{\mathrm{delta\,Ref}}))\right. \\
&\quad \left. - \left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot (1 - cos\,\alpha)\right)^2 \\
&\quad \cdot (s^2(\overline{F}) + u^2(F)) + (F \cdot (1 - cos\,(\alpha + \alpha_{\mathrm{delta\,Ref}})) \\
&\quad - F \cdot (1 - cos\,\alpha))^2 \cdot (s^2(\overline{L_1}) + u^2(L_1)) \\
&\quad + \left(\frac{-1}{2}F \cdot (1 - cos\,(\alpha + \alpha_{\mathrm{delta\,Ref}}))\right. \\
&\quad \left. + \frac{1}{2}F \cdot (1 - cos\,\alpha)\right)^2 \cdot (s^2(\overline{L_2}) + u^2(L_2)) \\
&\quad + \left(\frac{-1}{2}F \cdot (1 - cos\,(\alpha + \alpha_{\mathrm{delta\,Ref}}))\right. \\
&\quad \left. + \frac{1}{2}F \cdot (1 - cos\,\alpha)\right)^2 \cdot (s^2(\overline{L_3}) + u^2(L_3)) \\
&\quad + \left(F \cdot \left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot sin(\alpha + \alpha_{\mathrm{delta\,Ref}})\right. \\
&\quad \left. - F \cdot \left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot sin\,\alpha\right)^2 \cdot (s^2(\overline{\alpha}) + u^2(\alpha)) \\
&\quad + \left(F \cdot \left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot sin(\alpha + \alpha_{\mathrm{delta\,Ref}}) - 0\right)^2 \\
&\quad \cdot (s^2(\overline{\alpha}_{\mathrm{delta\,Ref}}) + u^2(\alpha_{\mathrm{delta\,Ref}}))
\end{aligned} \tag{28}$$

If necessary, the calculation must be carried out for both cases a) and b).

3.4 | Horizontal alignment without a reference plane

To calculate $K_{\mathrm{P\ without\ Ref}}$ the same relationship applies as in Chapter 3.3 and therefore the same measurement uncertainty components must be applied.

3.5 | Hanging free pendulum

When hanging free, the pendulum shall hang so that the striking edge is within $s_{\mathrm{hanging\ free\ pendulum}}$ = 2.5 mm of the position where it would just touch the test specimen [3, chapter 6.3.4]. The pendulum delivers the correct amount of energy at the bottom dead center, *Figure 6*. Deviations from this result in the following error $K_{\mathrm{P\ hanging\ free\ pendulum}}$:

$$K_{\mathrm{P\,hanging\,free\,pendulum}} = F \cdot l_2 \cdot (1 - cos\,\alpha_{\mathrm{hanging\,free\,pendulum}}) \tag{29}$$

with

$$\alpha_{\mathrm{hanging\,free\,pendulum}} = arcsin\frac{s_{\mathrm{hanging\,free\,pendulum}}}{l_2} \tag{30}$$

The result is:

$$\begin{aligned}
&u^2_{\mathrm{KP\,hanging\,free\,pendulum}}(y) \\
&= \sum_{i=1}^{5}\left(\frac{\partial K_{\mathrm{P\,hanging\,free\,pendulum}}}{\partial x_{\mathrm{i}}}\right)^2 \cdot u^2(x_{\mathrm{i}}) \\
&= \left(\left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot (1 - cos\,\alpha_{\mathrm{hanging\,free\,pendulum}})\right)^2 \\
&\quad \cdot (s^2(\overline{F}) + u^2(F)) \\
&\quad + (F \cdot (1 - cos\,\alpha_{\mathrm{hanging\,free\,pendulum}}))^2 \cdot (s^2(\overline{L_1}) + u^2(L_1)) \\
&\quad + \left(\frac{-1}{2}F \cdot (1 - cos\,\alpha_{\mathrm{hanging\,free\,pendulum}})\right)^2 \\
&\quad \cdot (s^2(\overline{L_2}) + u^2(L_2)) \\
&\quad + \left(\frac{-1}{2}F \cdot (1 - cos\,\alpha_{\mathrm{hanging\,free\,pendulum}})\right)^2 \\
&\quad \cdot (s^2(\overline{L_3}) + u^2(L_3)) \\
&\quad + \left(F \cdot \left(L_1 - \frac{L_2}{2} - \frac{L_3}{2}\right) \cdot sin\,\alpha_{\mathrm{hanging\,free\,pendulum}}\right)^2 \\
&\quad \cdot (s^2(\overline{\alpha}_{\mathrm{hanging\,free\,pendulum}}) + u^2(\alpha_{\mathrm{hanging\,free\,pendulum}}))
\end{aligned} \tag{31}$$

3.6 | Contact between striker and test piece

The striker shall make contact over the full thickness of test piece. To verify this the test piece usually will be

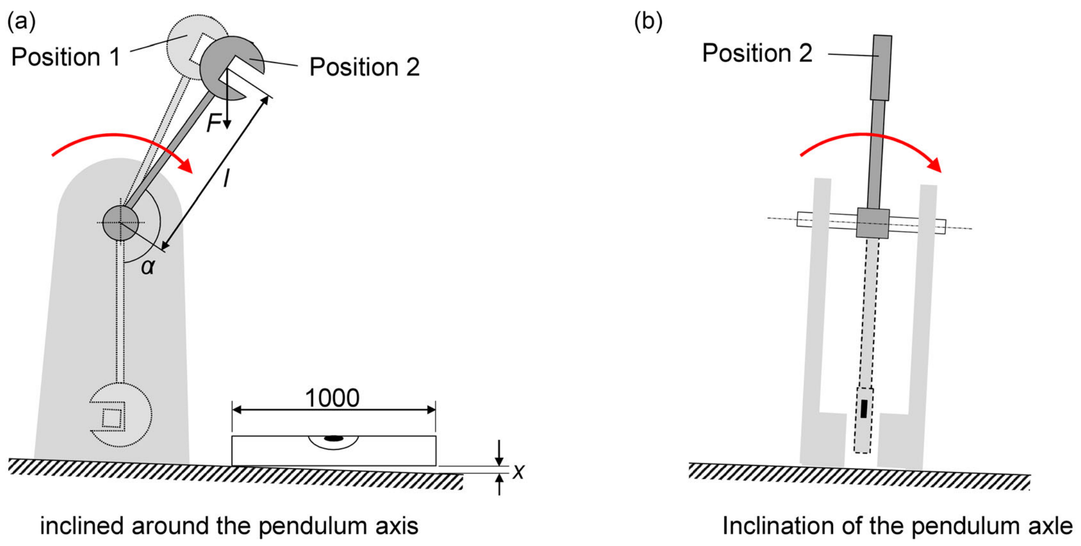

FIGURE 5 Horizontal reference plane.

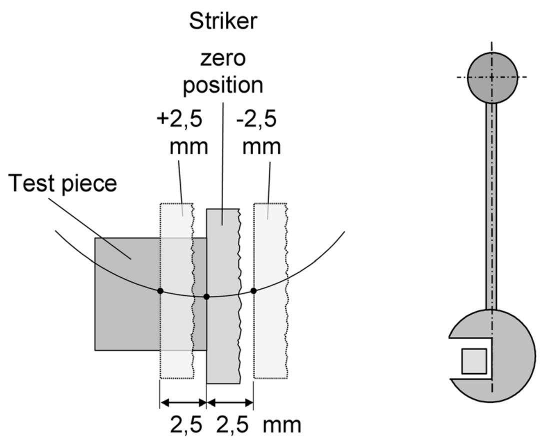

FIGURE 6 Free hanging pendulum.

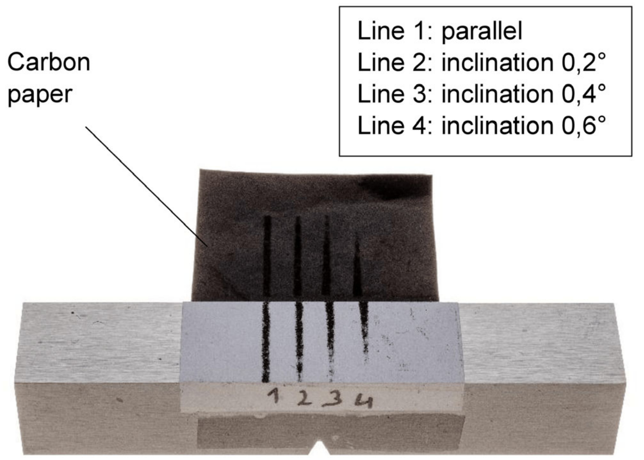

FIGURE 7 Contact line created with carbon paper at different inclinations of the striker.

wrapped with carbon paper, so the striker leaves a mark on the paper. At an inclination of about 0.5° is a safe indication possible, *Figure 7*.

To estimate the influence, empirical tests were carried out on a reference pendulum impact machine which has a higher accuracy as a regular one. In all tests certified reference test pieces of known energy were used, and changes, such as in this case between a correct striker and a manipulated striker, were recorded, *Figure 8*.

After each reconstruction, pendulum impact test was first carried out with certified reference test piece to ensure the necessary setting processes. It was also checked whether the standard deviations of the test pieces corresponded to those of the certified reference test pieces. The tests were conducted with significantly inflated values to make the influences measurable. However, these results are only approximations.

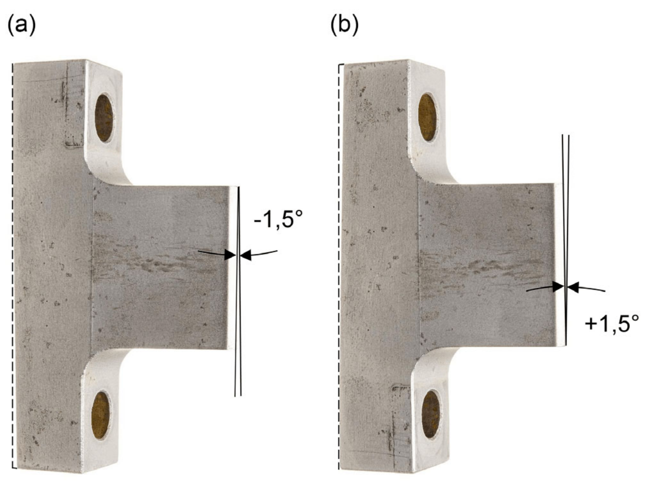

FIGURE 8 Manipulated striker in two installation positions.

In this case the test was performed with a significant higher inclination of the striker of ± 1,56°. It is clearly visible on the test pieces that the forces acting on the top side of the specimen in installation position a) and on the bottom side in installation position b) are significantly greater, *Figure 9*.

The test showed a change in the indicated energy of about 0.3 J and the influence on the displayed energy can be roughly estimated depending on the inclination of the striker $\alpha_{\text{contact striker}}$ using the following numerical equation:

$$K_{\text{S contact striker}} = \frac{\alpha_{\text{contact striker}}}{1.56°} \cdot 0.3\text{J} \tag{32}$$

The measurement uncertainty $u_{\text{contact striker}}$ is to be estimated from the reliability of the method of determining the contact line using carbon paper.

3.7 | Indicating equipment

The reading is taken either on an analog or digital display. The measurement uncertainty resulting from the analog indicating pointer is influenced by the estimable scale division, i.e., the resolution r (usually 1/5 or 1/10 of a division on the scale). For reading on a digital display, the digit step is used for r.

The following applies to the measurement uncertainty resulting from the Indicating equipment:

$$u_{\text{r}} = \frac{r}{2 \cdot \sqrt{3}} \tag{33}$$

3.8 | Loss due to friction

The loss due to friction consist of loss due to friction of indicating pointer and losses caused by bearing friction and air resistance.

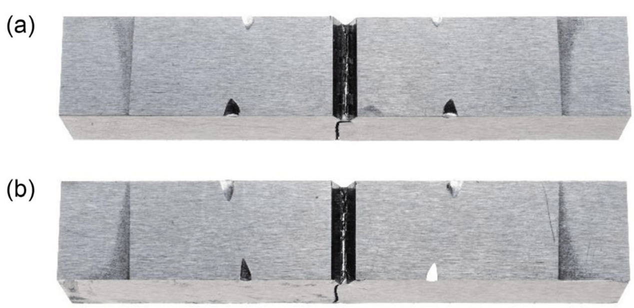

FIGURE 9 Test pieces after testing with manipulated striker in installation position a) and b).

$$p_{\text{total}} = p + p' \tag{34}$$

3.8.1 | Loss due to friction of indicating pointer

The friction loss due to friction of indicating pointer p is given by:

$$p = K_1 - K_2 \tag{35}$$

K_1 is the indicated absorbed energy of a test without a test piece in position with indicating pointer, K_2 is the indicated absorbed energy of a test without a test piece in position without indicating pointer [3, chapter 6.4.5.1].

The standard uncertainty is calculated as follows:

$$u_{\text{p}}^2(y) = \sum_{i=1}^{2} \left(\frac{\partial p}{\partial x_{\text{i}}}\right)^2 \cdot u^2(x_{\text{i}}) = \left(\frac{\partial p}{\partial K_1}\right)^2 \cdot (s^2(K_1) + u_{\text{r}}^2) + \left(\frac{\partial p}{\partial K_2}\right)^2 \cdot (s^2(K_2) + u_{\text{r}}^2) \tag{36}$$

or for the partial derivative:

$$u_{\text{p}}^2(y) = \sum_{i=1}^{2} \left(\frac{\partial p}{\partial x_{\text{i}}}\right)^2 \cdot u^2(x_{\text{i}}) = s^2(K_1) + s^2(K_2) + 2 \cdot u_{\text{r}}^2 \tag{37}$$

The reading uncertainty u_{r} is given by *equation (33)*

3.8.2 | Losses caused by bearing friction and air resistance

To determine the bearing friction and the air resistance p', the following relationship applies:

$$p' = \frac{1}{10} \cdot (K_3 - K_2) \tag{38}$$

K_3 is the indicated absorbed energy after 11 half swings when the machine is operated in the normal manner without a test piece in position and without resetting the indication mechanism [3, chapter 6.4.5.2].

The standard uncertainty is calculated as follows:

$$u_{\text{p}'}^2(y) = \sum_{i=1}^{2} \left(\frac{\partial p'}{\partial x_{\text{i}}}\right)^2 \cdot u^2(x_{\text{i}}) = \left(\frac{\partial p'}{\partial K_3}\right)^2 \cdot (s^2(K_3) + u_{\text{r}}^2) + \left(\frac{\partial p'}{\partial K_2}\right)^2 \cdot (s^2(K_2) + u_{\text{r}}^2) \tag{39}$$

or for the partial derivative:

$$u_{p'}^2(y) = \sum_{i=1}^{2} \left(\frac{\partial p'}{\partial x_i}\right)^2 \cdot u^2(x_i) \\ = \frac{1}{100} \cdot (s^2(K_3) + s^2(K_2) + 2 \cdot u_r^2) \tag{40}$$

3.9 | Distance to the centre of percussion from the axis of rotation

The aim of the pendulum impact test is to subject the material – the test piece – to an impact load. The pendulum used behaves as if the entire pendulum mass were concentrated at the center of impact [11]. The distance from the center of impact is therefore equal to the length of the mathematical pendulum with the same period of pendulum. A mathematical pendulum is characterized by the fact that during oscillation the frequency depends only on the length of the pendulum, but not on the initial deflection or the attached mass, *Figure 10*.

From the equilibrium of forces and moments, the error results K_{l1} from the deviation from the mathematical pendulum is given by:

$$K_{l1} = \left(\frac{l_1}{l} - 1\right) \cdot K_{Pot} \tag{41}$$

l_1 is calculated during calibration from the time t for a complete swinging (g is the acceleration of gravity) (3, chapter 6.4.6):

$$l_1 = \frac{g \cdot t^2}{4\pi^2} \tag{42}$$

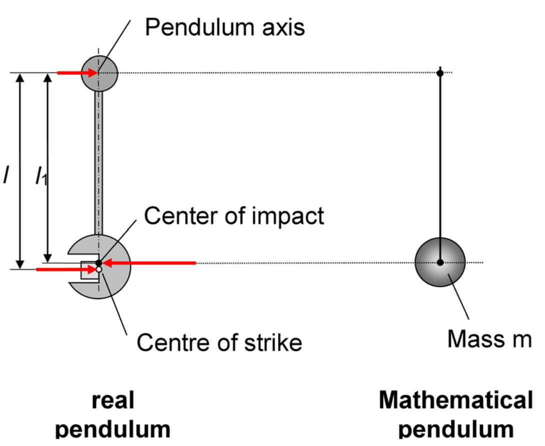

FIGURE 10 Comparison real pendulum and mathematical pendulum.

or simplified using the numerical equation (with t in seconds and l_1 in meters)

$$l_1 = 0.2485 \cdot t^2 \tag{43}$$

For the calculation of the partial derivative, it should be noted that the factor 0.2485 has the unit m/s^2.

together with *equations* (41), (43) and (8) we get

$$K_{l1} = \frac{0.2485 \cdot t^2}{L_1 - \frac{L_2}{2} - \frac{L_3}{2}} \cdot K_{Pot} - K_{Pot} \tag{44}$$

The measurement uncertainty is calculated as follows:

$$u_A^2(y) = \sum_{i=1}^{5} \left(\frac{\partial K_{l1}}{\partial x_i}\right)^2 \cdot u^2(x_i) \\ = \left(\frac{\partial K_{l1}}{\partial t}\right)^2 \cdot (s^2(\bar{t}) + u_{standard}^2(t)) \\ + \left(\frac{\partial K_{l1}}{\partial L_1}\right)^2 \cdot (s^2(\overline{L_1}) + u_{standard}^2(L_1)) \\ + \left(\frac{\partial K_{l1}}{\partial L_2}\right)^2 \cdot (s^2(\overline{L_2}) + u_{standard}^2(L_2)) \\ + \left(\frac{\partial K_{l1}}{\partial L_3}\right)^2 \cdot (s^2(\overline{L_3}) + u_{standard}^2(L_3)) \\ + \left(\frac{\partial K_{l1}}{\partial K_{Pot}}\right)^2 \cdot (s^2(K_{Pot})) \tag{45}$$

or:

$$u_A^2(y) = \sum_{i=1}^{5} \left(\frac{\partial K_{l1}}{\partial x_i}\right)^2 \cdot u^2(x_i) \\ = \left(\frac{2 \cdot 0.2485 \cdot t}{L_1 - \frac{L_2}{2} - \frac{L_3}{2}} \cdot K_{Pot}\right)^2 \cdot (s^2(\bar{t}) + u_{standard}^2(t)) \\ + \left(\frac{-0.2485 \cdot t^2 \cdot K_{Pot}}{(L_1 - \frac{L_2}{2} - \frac{L_3}{2})^2}\right)^2 \cdot (s^2(\overline{L_1}) + u_{standard}^2(L_1)) \\ + \left(\frac{0.2485 \cdot t^2 \cdot K_{Pot} \cdot \frac{1}{2}}{(L_1 - \frac{L_2}{2} - \frac{L_3}{2})^2}\right)^2 \cdot (s^2(\overline{L_2}) + u_{standard}^2(L_2)) \\ + \left(\frac{0.2485 \cdot t^2 \cdot K_{Pot} \cdot \frac{1}{2}}{(L_1 - \frac{L_2}{2} - \frac{L_3}{2})^2}\right)^2 \cdot (s^2(\overline{L_3}) + u_{standard}^2(L_3)) \\ + \left(\frac{0.2485 \cdot t^2}{L_1 - \frac{L_2}{2} - \frac{L_3}{2}}\right)^2 \cdot (s^2(K_{Pot})) \tag{46}$$

K_{Pot} is the potential energy of the pendulum impact machine.

The measurement uncertainty of the time measurement (usually stopwatch) can be specified as follows:

$$u_{\mathrm{t}}^2 = u_{\text{standard}}^2 + u_{\text{deviation standard}}^2 + \frac{1}{3}a_{\text{resolution standard}}^2 + \frac{1}{3}a_{\text{reaction time}}^2 \tag{47}$$

In addition to the measurement uncertainty of the calibration of the standard u_{standard} and the deviation $u_{\text{deviation standard}}$ determined during calibration of the standard, the resolution of the standard $u_{\text{resolution standard}}$ and the reaction time when using the stopwatch $u_{\text{reaction time}}$ must also be taken into account. The components are to be used for the time of one swing, not for the time measurement of 100 swings T.

3.10 | Radius of striking edge

The radius of a 2 mm striker should be according ISO 148-2 2.00 mm, with an upper accepted value of 2.50 mm [3, *Table 3*].

3.10.1 | Calculation using finite element simulation

To estimate the influence, an finite element simulation was performed on a 2 mm striker [12]. The difference of the energy between the 2.00 mm and 2.50 mm radius was determined to 0.4 %, *Figure 11*.

Thereby, the influence of the 2 mm striker on the energy can be estimated as a numerical equation as follows

$$K_{\text{S radius striker}} = (r_{\text{striker}} - 2\,\text{mm}) \cdot 0.008 \cdot K_{\text{S}} \tag{48}$$

The measurement uncertainty of using the radius gauge can be estimated as follows:

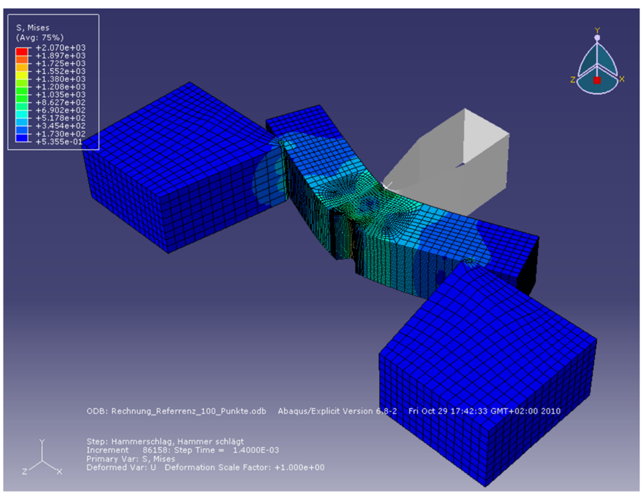

FIGURE 11 Simulation of a pendulum impact test.

$$u_{\text{radius striker}}^2 = u_{\text{standard}}^2 + u_{\text{deviation standard}}^2 + \frac{1}{3}a_{\text{increment standard}}^2 \tag{49}$$

Here, the uncertainty of the calibration of the radius gauge u_{standard}, the component of the uncorrected deviation $u_{\text{deviation standard}}$ and the increment of the available gauges $a_{\text{increment standard}}$ are influencing factors. These mm values must then be converted into energy units using the equivalent relationship from *equation (48)* via *(50)*.

$$K_{\text{S radius striker}} = \frac{\Delta r_{\text{striker}}}{0.5\,\text{mm}} \cdot 0.004 \cdot K_{\text{S}} \tag{50}$$

$\Delta r_{\text{striker}}$ is the deviation to the nominal radius 2.00 mm.

3.10.2 | Comparison with proficiency tests

Evaluations of conducted proficiency tests for identical sample material High and Low confirm this dependence of the striker radius on energy [13 - 16], *Table 1*. The certified values were determined for 2 mm strikers and 8 mm strikers.

If the change from 2 mm to 8 mm is related to the change from 2.00 mm to 2.50 mm and to the same energy values, this also results in an energy change of 0.4 %, which is consistent with the results of the finite element simulation.

3.11 | Angle of striker

To examine the influence of the angle of striker on a 2 mm striker, an finite element simulation was also conducted [12]. Here, the angle of striker was changed from the defined value of 30° to 31°, resulting in a change in impact energy of 0.02 % [3]. This influence $K_{\text{S angle striker}}$ is therefore negligible.

3.12 | Line of contact of the striker perpendicular to test piece

The angle between the line of contact of the striker and the horizontal axis of the test piece shall be 90° ± 2° [3, chapter 6.4.8]. The test is usually carried out very imprecisely using the mark left on the sample by the carbon paper.

To verify the influence of this effect, tests on a reference pendulum impact machine were made. The striker was turned by 5°, *Figure 12*.

TABLE 1 Proficiency test with 2 mm and 8 mm striker.

Striker	High 2411 HM	Low 2411 LM
2 mm	121 J	19.2 J
8 mm	127 J	18.4 J

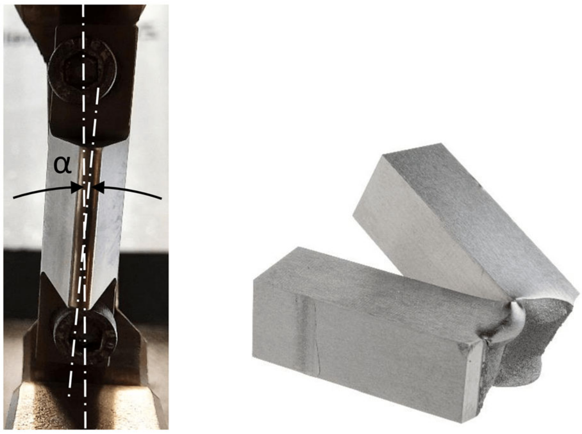

FIGURE 12 Turned striker and broken test piece.

The result of the recorded values (−0.5 J and −0.6 J) can be described as a numerical value equation as follows, *Table 2*:

$$K_{S\,\text{line of contact High}} = \frac{\alpha_{\text{line of contact}}}{5°} \cdot (-0.5\,\text{J})$$
$$K_{S\,\text{line of contact Low}} = \frac{\alpha_{\text{line of contact}}}{5°} \cdot (-0.6\,\text{J}) \quad (51)$$

The measurement uncertainty of using the angle meter can be estimated as follows:

$$u^2_{\text{line of contact}} = u^2_{\text{standard}} + u^2_{\text{deviation standard}} + \frac{1}{3}a^2_{\text{scale standard}} + \frac{1}{3}a^2_{\text{measuring angle}} \quad (52)$$

Here, the scale of angle meter $a_{\text{scale standard}}$ and uncertainty of reproducibility of using the angle meter $a_{\text{measuring angle}}$ are considered. Here, an estimate of reproducibility of 0.3° to 0.5° would be appropriate.

3.13 | Parallel test piece supports without offset

The planes containing the support surfaces shall be parallel and the distance between them shall not exceed 0.1 mm [3, chapter 6.5.2].

The empirical investigation with a sample placed with an angle of 3.85° (offset $s_{\text{offset support}} = 3.2\,\text{mm}$) on a reference pendulum impact machine which showed a change of the indicated energy 1.1 J and −0.6 J and so a numerical value equation can be described:

TABLE 2 Results with rotated striker by 5°.

Energy level	Perfect aligned striker 0°	Rotated striker by 5°	Change
High	119.8 J	119.3 J	- 0.5 J
Low	19.5 J	18.9 J	- 0.6 J

$$K_{S\,\text{offset support High}} = \frac{s_{\text{offset support}}}{3.2\,\text{mm}} \cdot (+1.1\,\text{J})$$
$$K_{S\,\text{offset support Low}} = \frac{s_{\text{offset support}}}{3.2\,\text{mm}} \cdot (-0.6\,\text{J}) \quad (53)$$

3.14 | Axis of the test piece parallel to the axis of rotation

Supports shall be such that the axis of the test piece is parallel to the axis of rotation of the pendulum within 3/1000 [3, chapter 6.5.2]

Here, the relationship from Chapter 3.13 is used. α_{axis} is the inclination in °.

$$K_{S\,\text{axis High}} = \frac{\alpha_{\text{axis}}}{3.85°} \cdot (+1.1\,\text{J})$$
$$K_{S\,\text{axis Low}} = \frac{\alpha_{\text{axis}}}{3.85°} \cdot (-0.6\,\text{J}) \quad (54)$$

3.15 | Parallel anvils without offset

The planes containing the anvil surfaces facing the test piece shall be parallel and the distance between them shall not exceed 0.1 mm [3, chapter 6.5.3]

To assess this requirement, tests were conducted on the reference pendulum impact machine. For this purpose, we lay underneath the anvil a 0.50 mm thick brass sheet, *Figure 13*.

The resulting of the recorded values (+2.3 J and −0.4 J) can be described as a numerical value equation as follows:

$$K_{S\,\text{offset anvil High}} = \frac{s_{\text{offset anvil}}}{0.5\,\text{mm}} \cdot (+2.3\,\text{J})$$
$$K_{S\,\text{offset anvil Low}} = \frac{s_{\text{offset anvil}}}{0.5\,\text{mm}} \cdot (-0.4\,\text{J}) \quad (55)$$

3.16 | Angle between anvil and test piece supports

If the required 90° angle between anvil and test piece supports is not met, the specimen will be pressed against the anvil during impact [3, chapter 6.5.3]. This causes that the test piece will move slightly upward, resulting in a slight change of the energy.

The changing of the energy is given by:

$$K_{P\,\text{anvil, suport}} = -F \cdot \Delta l_2 \cdot (1 - \cos\alpha) \quad (56)$$

and the height difference is:

$$\Delta l_2 = 10\,\text{mm} \cdot \tan\alpha_{\text{anvil, suport}} \quad (57)$$

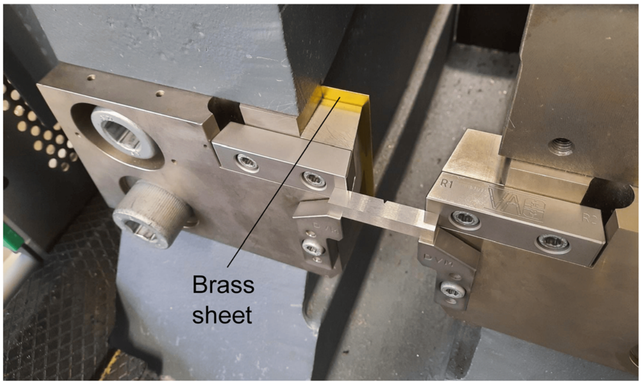

FIGURE 13 With brass sheet supported left anvil for manipulation.

3.17 | Distance between anvils

The distance between the anvils is defined between 40.00 mm and 40.20 mm [3]. Because the user wants to have as much flexibility as possible the value is usually set to 40.10 mm, *Figure 14*.

To determine the effect of values deviating from the target value, tests were conducted on a reference pendulum impact machine. The optimal distance of 40.10 mm was increased by 0.50 mm to 40.60 mm. The result of the test was −1.0 J and +0.1 J. The following numerical dependences were obtained:

$$\begin{aligned} K_{\mathrm{S\,distance\,anvils\,High}} &= \frac{l_{\mathrm{distance\,anvils}} - 40.1\,\mathrm{mm}}{0.5\,\mathrm{mm}} \cdot (-1.0\,\mathrm{J}) \\ K_{\mathrm{S\,distance\,anvils\,Low}} &= \frac{l_{\mathrm{distance\,anvils}} - 40.1\,\mathrm{mm}}{0.5\,\mathrm{mm}} \cdot (+0.1\,\mathrm{J}) \end{aligned} \tag{58}$$

3.18 | Striker needs to pass the anvil in the middle

The pendulum shall be located so that the centre of the striker and the centre of the gap between the anvils are coincident to within 0.5 mm [3, chapter 6.3.7].

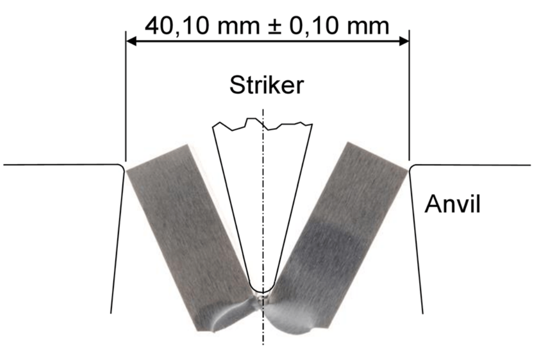

FIGURE 14 Distance between anvils.

If the striker passes the anvil off-center, the distance is larger on one side of the anvil and smaller on the other. This effect is very similar to the situation where the distance between anvils is reduced, compare Chapter 3.17.

So the formula (58) can be used equivalent to determine $K_{\mathrm{S\ striker\ off\text{-}center}}$.

3.19 | Axial play in the pendulum bearings

To check whether the axial play complies with the limit value, the pendulum is subjected to a defined transverse force at the point of impact.

Any axial movement of the pendulum would cause that the centre of strike would be off-center, which would have an effect as described in Chapter 3.18 and could be estimated using formula (58) to calculate $K_{\mathrm{S\ axial\ play}}$.

3.20 | Radial play in the pendulum bearings

To check whether the radial play of the shaft in the pendulum bearings complies with the limit value, the pendulum is subjected to a defined transverse force at the point of impact, *Figure 15*.

Two effects can occur. First, the impact point would no longer be in the center, which would have for $K_{\mathrm{S\ radial\ play\ off\text{-}center}}$ an effect corresponding to Chapter 3.18 and could be estimated using formula (58).

If the radial play $s_{\mathrm{radial\ play}}$ is detected, the eccentricity is:

$$s_{\mathrm{deltabearing}} = s_{\mathrm{radialplay}} \cdot \frac{l_2}{s_{\mathrm{bearing}}} \tag{59}$$

The second effect $K_{\mathrm{S\ radial\ play\ inclined}}$ would be a tilt of the striker, as described in Chapter 3.12. A radial play of $s_{\mathrm{radial\ play}}$ would result in an inclined position $\alpha_{\mathrm{radial\ play}}$ of the pendulum axis or of the pendulum rod and thus of the striker:

$$\alpha_{\mathrm{radialplay}} = arctan \frac{s_{\mathrm{radialplay}}}{s_{\mathrm{bearing}}} \tag{60}$$

The effect can be estimated equivalently to formula (51).

3.21 | Radius of anvils

The required dimension of the anvils is 1.00 mm with a maximum value of 1.50 mm [3].

The influence of the radius of anvils was determined by conducting tests on the reference pendulum impact

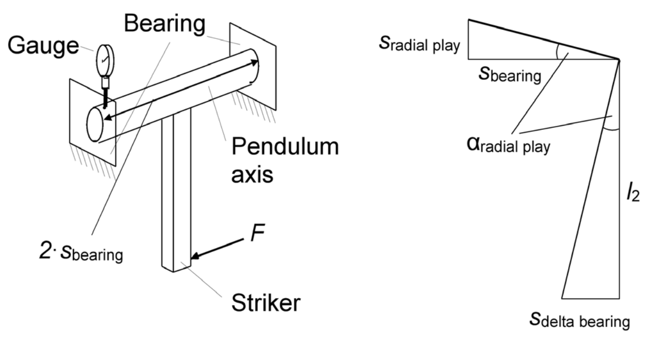

FIGURE 15 Radial play in the pendulum bearings.

machine. For this purpose, the manufacturer was commissioned for production of special anvils with a radius of 2.00 mm to determine the deviations.

The experiment yielded a result of −5.8 J and −1.4 J and the result can be described in the following numerical equation:

$$K_{\text{S radius anvil High}} = \frac{r_{\text{anvil}} - 1\,\text{mm}}{1\,\text{mm}} \cdot (-5.8\,\text{J})$$
$$K_{\text{S radius anvil Low}} = \frac{r_{\text{anvil}} - 1\,\text{mm}}{1\,\text{mm}} \cdot (-1.4\,\text{J}) \quad (61)$$

r_{anvil} is the radius of the anvil and is used in mm. This means that abrasion on the anvils from 1.00 mm to 1.50 mm, depending on the energy level, can lead to a very large error rate of up to 2.9 J – although the radius is still within the permitted tolerance.

According formula (49) the uncertainty of the measurement of the radius $u_{\text{radius anvil}}$ needs to be calculated and similar converted in energy units. Significant components of 0.8 J ($k = 1$) can also occur for the measurement uncertainties due to the large influence.

So it is also for the user of the test laboratory very important to take care on the radius of anvils.

3.22 | Influences not to be considered additionally

According to the standard the following points must also be checked during calibration:

- The axis of rotation of the pendulum shall be parallel to the reference plane to within 2/1000 [3, chapter 6.3.2]
- The plane of swing of the pendulum shall be 90.0° ± 0.1° to the axis of rotation [3, chapter 6.3.5]

However, if these were determined for the combined instrument bias, they would be considered twice, because they have already been recorded elsewhere in the standard.

Therefore, it is not taken into account here.

3.23 | Negligible influences

The following points to be checked according to the standard are assumed to have no influence on the combined instrument bias if the required boundary conditions are met:

- Foundation / installation (mass of the foundation, bolts are torqued, external vibrations), Note: If the screws are loose, this can have a significant impact on the result,
- Mass of the base of the machine framework,
- Velocity at impact (because it is a process parameter which has no influence on the impact process),
- The maximum width of that portion of the striker passing between the anvils shall be at least 10 mm but not greater than 18 mm,
- Mechanism for releasing the pendulum,
- Brake mechanism,
- Angle of taper of anvil,
- Width of striker.

4 | RESULT

4.1 | Combined instrument bias

According to *equation* (62), all determined deviations, which also have a reliable significance with regard to the amount and the sign, can be added as a combined instrument bias z:

$$z = A + K_{\text{error indicated energy}} + K_{\text{P Ref a)}} + K_{\text{P Ref b)}} + K_{\text{P without Ref}} + K_{\text{P hanging free pendulum}} + p + K_{11} \quad (62)$$

where

A	Deviation of potential energy,
$K_{\text{error indicated energy}}$	Error of indicated absorbed energy,
$K_{\text{P Ref a)}}$	Horizontal reference plane, axis a),
$K_{\text{P Ref b)}}$	Horizontal reference plane, axis b),
$K_{\text{P without Ref}}$	Horizontal alignment without a reference plane,
$K_{\text{P hanging free pendulum}}$	Hanging free pendulum,
p	Loss due to friction,
K_{11}	Distance to the centre of percussion from the axis of rotation.

It should be noted that the user of the pendulum impact machine may need to perform a correction of a systematic bias. Therefore, only components with reliable significance may be considered at this point.

According to Chapter 4.2, the following factors are included in the measurement uncertainty as a rectangular distribution:

$K_{\text{P measuring method}}$	Force measuring method,
$K_{\text{P Pos}}$	Positioning of force-proving instrument,
$K_{\text{P delta F}}$	Horizontal alignment of the pendulum,

$K_{S\ \text{contact striker}}$ Contact between striker and test piece,
$K_{S\ \text{radius striker}}$ Radius of striking edge,
$K_{S\ \text{angle striker}}$ Angle of striker,
$K_{S\ \text{line of contact}}$ Line of contact of the striker perpendicular to test piece,
$K_{S\ \text{offset support}}$ Parallel test piece supports without offset,
$K_{S\ \text{axis}}$ Axis of the test piece parallel to the axis of rotation,
$K_{S\ \text{offset anvil}}$ Parallel anvils without offset,
$K_{P\ \text{anvil, support}}$ Angle between anvil and test piece supports,
$K_{S\ \text{distance anvil}}$ Distance between anvils,
$K_{S\ \text{striker off-center}}$ Striker needs to pass the anvil in the middle,
$K_{S\ \text{axial play}}$ Axial play in the pendulum bearings,
$K_{S\ \text{radial play off-center}}$ Radial play in the pendulum bearings (out of center),
$K_{S\ \text{radial play inclined}}$ Radial play in the pendulum bearings (tilt),
$K_{S\ \text{radius anvil}}$ Radius of anvils.

4.2 | Combined standard uncertainty

For the combined standard uncertainty u_c for z, the measurement uncertainty components and the components without reliable significance are summed as a rectangular distribution:

$$\begin{aligned}
u_c^2 = {} & u_A^2 + u_{\text{KP Pos}}^2 + u_{\text{KP delta F}}^2 + u_{\text{K error indicated energy}}^2 \\
& + u_{\text{KP Ref}}^2 + u_{\text{KP without Ref}}^2 + u_{\text{KP hanging free pendulum}}^2 \\
& + u_{\text{contct striker}}^2 + u_p^2 + u_{p\prime}^2 + u_{\text{K l1}}^2 + u_{\text{radius striker}}^2 \\
& + u_{\text{angle striker}}^2 + u_{\text{line of contact}}^2 + u_{\text{offset support}}^2 + u_{\text{axis}}^2 \\
& + u_{\text{offset anvil}}^2 + u_{\text{anvil, support}}^2 + u_{\text{distance anvil}}^2 \\
& + u_{\text{striker off}-\text{center}}^2 + u_{\text{axial play}}^2 + u_{\text{radial play off}-\text{ceter}}^2 \\
& + u_{\text{radial play inclined}}^2 + u_{\text{radius anvil}}^2 + u_r^2 \\
& + \frac{1}{3}K_{\text{P measuring method}}^2 + \frac{1}{3}K_{\text{P Pos}}^2 + \frac{1}{3}K_{\text{P delta F}}^2 \\
& + \frac{1}{3}K_{\text{S contact striker}}^2 + \frac{1}{3}K_{\text{S radius striker}}^2 + \frac{1}{3}K_{\text{S angle striker}}^2 \\
& + \frac{1}{3}K_{\text{S line of contact}}^2 + \frac{1}{3}K_{\text{S offset support}}^2 + \frac{1}{3}K_{\text{S axis}}^2 \\
& + \frac{1}{3}K_{\text{S offset anvil}}^2 + \frac{1}{3}K_{\text{P anvil, support}}^2 + \frac{1}{3}K_{\text{S distance anvil}}^2 \\
& + \frac{1}{3}K_{\text{S striker of}-\text{center}}^2 + \frac{1}{3}K_{\text{S axial play}}^2 + \frac{1}{3}K_{\text{S radial off}-\text{center}}^2 \\
& + \frac{1}{3}K_{\text{S radial play inclined}}^2 + \frac{1}{3}K_{\text{S radius anvil}}^2
\end{aligned} \tag{63}$$

where

u_A Uncertainty of deviation of potential energy,
$u_{\text{KP Pos}}$ Uncertainty of force measuring method,
$u_{\text{KP delta F}}$ Uncertainty of horizontal alignment of the pendulum,
$u_{\text{K error indicated energy}}$ Uncertainty of absorbed energy,
$u_{\text{KP Ref}}$ Uncertainty of horizontal reference plane,
$u_{\text{KP without Ref}}$ Uncertainty of horizontal alignment without a reference plane,
$u_{\text{KP hanging free pendulum}}$ Uncertainty of hanging free pendulum,
$u_{\text{contact striker}}$ Uncertainty of contact between striker and test piece,
u_p Uncertainty of loss due to friction of indicating pointer,
$u_{p'}$ Uncertainty of loss due to friction and air resistance,
$u_{\text{K l1}}$ Uncertainty of distance to the centre of percussion from the axis of rotation (math. Pendulum),
$u_{\text{radius striker}}$ Uncertainty of radius of striking edge,
$u_{\text{angle striker}}$ Uncertainty of line of contact of the striker perpendicular to test piece,
$u_{\text{offset support}}$ Uncertainty of parallel test piece supports without offset,
u_{axis} Uncertainty of axis of the test piece parallel to the axis of rotation,
$u_{\text{offset anvil}}$ Uncertainty of parallel anvils without offset,
$u_{\text{anvil, support}}$ Uncertainty of angle between anvil and test piece supports,
$u_{\text{distance anvil}}$ Uncertainty of distance between anvils,
$u_{\text{striker off-center}}$ Uncertainty of striker needs to pass the anvil in the middle,
$u_{\text{axial play}}$ Uncertainty of axial play in the pendulum bearings,
$u_{\text{radial play off–center}}$ Uncertainty of radial play in the pendulum bearings (out of center),
$u_{\text{radial play inclined}}$ Uncertainty of radial play in the pendulum bearings (tilt),
$u_{\text{radius anvil}}$ Uncertainty of radius of anvils,
u_r Uncertainty of indicating equipment.

It should be noted that some components have different amounts for the high and low energy levels.

5 | DETERMINATION OF DIFFERENT INFLUENCING PARAMETERS TO THE UNCERTAINTY BY EXPERIMENTAL TESTS

To illustrate which component causes which measurement uncertainty, an example of the calibration of a 300 J pendulum impact machine[3] was used.

TABLE 3 Results of the calibration.

Requirement of ISO 148-2	capter in ISO 148-2	capter this publication	bias K_S High in J	bias K_S Low in J	uncert. u High in J	uncert. u Low in J	ratio of uncertainty in %
Horizontal reference plane a)	6.3.3	3.3	-0.08	-0.08	0.03	± 0.03	1.3
Horizontal reference plane b)	6.3.3	3.3	-0.08	-0.08	0.03	± 0.03	1.3
Horizontal alignment without a reference plane	6.3.3	3.4	-0.15	-0.15	0.03	± 0.03	2.2
Hanging free pendulum	6.3.4	3.5	0.00	0.00	0.00	± 0.00	0.0
Contact between striker and test piece	6.3.6	3.6	0.10	0.10	0.06	± 0.06	1.8
Striker needs to pass the anvil in the middle	6.3.7	3.18	-0.20	0.02	0.12	± 0.01	2.1
Axial play in the pendulum bearings	6.3.8	3.19	-0.08	0.01	0.02	± 0.00	0.6
Radial play in the pendulum bearings	6.3.9	3.20	-0.35	0.03	0.11	± 0.01	3.0
Deviation of potential energy	6.4.2	3.1.1	-0.51	-0.51	0.33	± 0.33	9.9
Positioning of force-proving instrument	6.4.2	3.1.3	0.40	0.40	0.23	± 0.23	7.5
Force measuring method	6.4.2	3.1.2	0.21	0.21			2.5
Horizontal alignment of the pendulum	6.4.2	3.1.4	0.00	0.00	0.00	± 0.00	0.0
Absorbed energy	6.4.3	3.2	-1.09	-1.09	0.36	± 0.36	17.2
Loss due to friction of indicating pointer	6.4.5	3.8.1	-0.24	-0.24	0.22	± 0.22	5.4
Losses caused by bearing friction and air resistance	6.4.5	3.8.2	-1.02	-1.02	0.02	± 0.02	12.3
Distance to the centre of percussion	6.4.6	3.9	-1.16	-1.16	0.38	± 0.38	18.3
Radius of striking edge	6.4.7	3.10	0.24	0.04	0.14	± 0.02	2.6
Angle of striker	6.4.7	3.11	0.00	0.00	0.01	± 0.01	0.1
Line of contact of striker perpendicular to test piece	6.4.8	3.12	0.00	0.00	0.03	± 0.04	0.4
Parallel test piece supports without offset	6.5.2	3.13	0.03	-0.02	0.01	± 0.00	0.4
Axis of the test piece parallel to the axis of rotation	6.5.2	3.14	0.01	0.00	0.01	± 0.00	0.1
Parallel anvils without offset	6.5.3	3.15	0.46	-0.08	0.08	± 0.01	3.8
Angle between anvil and test piece supports	6.5.3	3.16	-0.01	-0.01	0.00	± 0.00	0.1
Distance between anvils	6.5.3	3.17	0.00	0.00	0.04	± 0.00	0.2
Radius of anvils	6.5.3	3.21	0.00	0.00	0.84	± 0.20	6.2
Indicating equipment	6.6.1	3.7			0.06	± 0.06	0.7

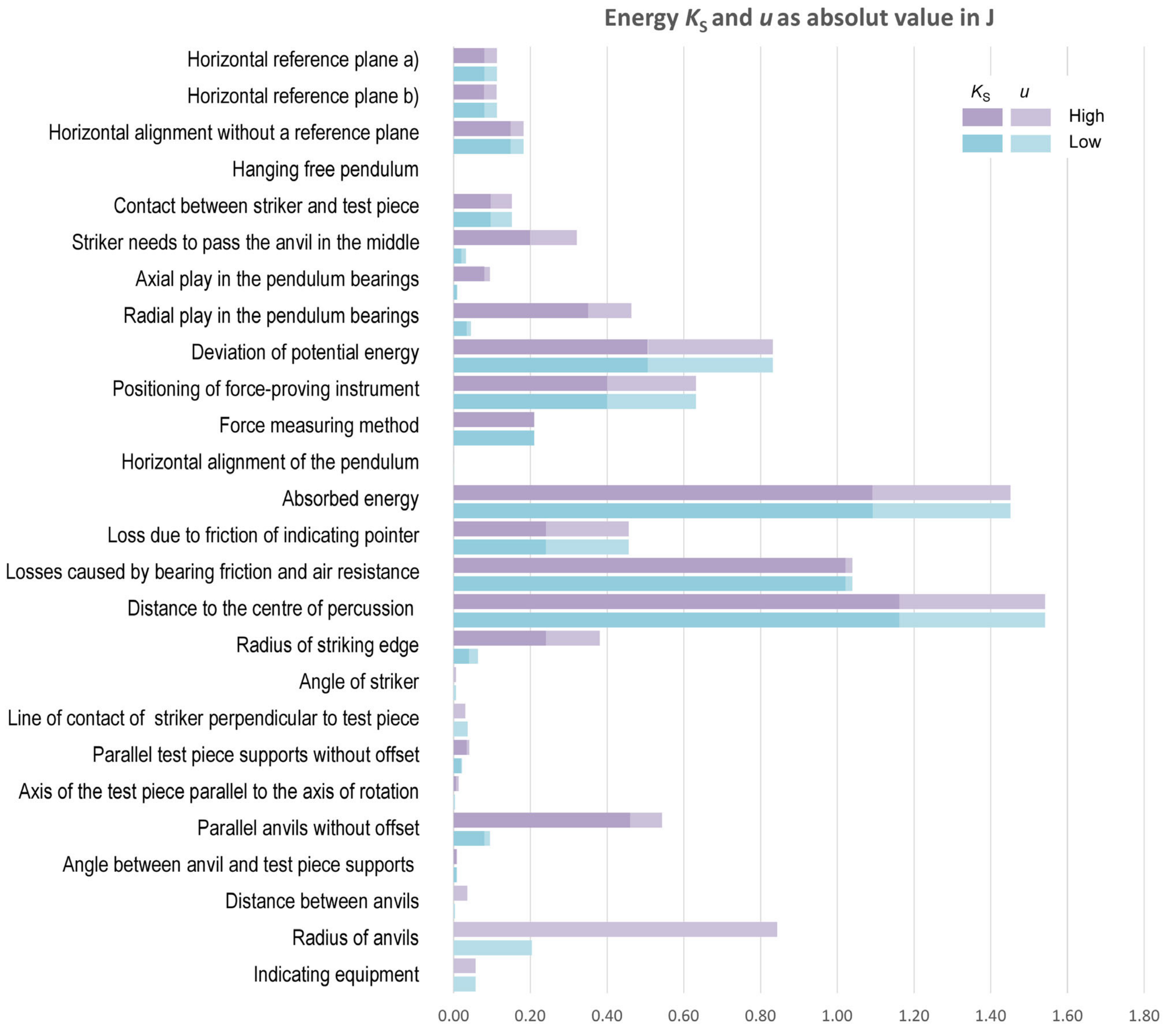

FIGURE 16 Graphical representation of the results.

Due to the partly different values for high and low energy levels there will be a separation between high and low energy values for the results, *Table 3*, *Figure 16*. Here, the bias of the indicated energy K_S and the associated measurement uncertainty u are shown depending on the respective influencing factor. The last column provides an indication of which influencing factors have the greatest proportional influence.

The result of the combined instrument bias z according to formula (62) is for this example:

$$z = -3.3\,\mathrm{J} \tag{64}$$

The combined standard uncertainty u_c for z is according formula (63)

$$u_{\mathrm{c\,High}} = \sqrt{\sum u_x^2 + \frac{1}{3}K_{\mathrm{S}x}^2} = \sqrt{\sum 0.217\,\mathrm{J}^2 + 1.271\,\mathrm{J}^2} = 1.22\,\mathrm{J}$$
$$u_{\mathrm{c\,Low}} = \sqrt{\sum u_x^2 + \frac{1}{3}K_{\mathrm{S}x}^2} = \sqrt{\sum 0.074\,\mathrm{J}^2 + 0.534\,\mathrm{J}^2} = 0.78\,\mathrm{J} \tag{65}$$

So the result is:

$$z_{\mathrm{High}} = -3.3\,\mathrm{J} \pm 1.2\,\mathrm{J}$$
$$z_{\mathrm{Low}} = -3.3\,\mathrm{J} \pm 0.8\,\mathrm{J} \tag{66}$$

The results are evaluated in the following chapter.

6 | CONCLUSION

With this shown approach, it is possible to present the effect of all calibrated points of the standard on the indicated absorbed energy and to calculate so the bias and to estimate the measurement uncertainty of a pendulum impact machine.

The presented numerical example of a concrete calibration has shown that many influences that have so far not been considered must be considered additionally, whereas some components can also be ignored.

The following points are of great relevance (see the references to the previous chapters):

- Determination of potential energy; however, this is mostly considered (3.1.1).
- Positioning of the force-proving instrument; the transmission of the centre of strike and the positioning of the force-proving instrument is clearly noticeable (3.1.3).
- Force measuring method; it as has been shown, that the length of the stilt for application of forces, the vertical alignment of the stilt and the sensitivity to transverse forces may have a significant impact with up to 0.7 %. This point must be given more importance in the future (3.1.2).
- The determination according the standard of the error of the displayed absorbed energy is hereby confirmed (3.2).
- Loss due to friction of indicating pointer (3.8.1) and losses caused by bearing friction and air resistance (3.8.2) must be considered.
- The deviation from the mathematical pendulum is determined by measuring the pendulum length l_1 over the period of the pendulum using a stopwatch. The importance of this difference was previously unknown (3.9).
- Deviations from the ideal radius of the striker edge also affect the indicated absorbed energy (3.10).
- This study has shown that the radius of anvils, which has a narrowly toleranced dimension, has an important part and should measured as good as possible. Some radius gauge allows only to check the limit values of 1.0 mm and 1.5 mm. In this case, a radius gauge in 0.1 mm increments is strongly recommended. Even a change from the ideal dimension of 1.0 mm to the limit of 1.5 mm can cause a deviation of 2.9 J (3.21).
- The requirement that the angle of striker shall make contact over the full thickness of test piece is not negligible, especially because it could be indicated by the carbon paper inaccurate. A save indication is only with an accuracy of 0.5° possible. So, this uncertainty needs to be considered. (3.6).
- The study has shown that the anvil should be in one plane. The standard allows to be within 0.1 mm, but even this offset can cause a deviation of 0.5 J (3.15).
- A possible radial play in the pendulum bearings can cause a deviation of 1 J (3.20).
- The optimal alignment of the distance between anvils and that the striker needs to pass the anvil in the middle is also very important, because deviations of 0.2 J to 1 J can occur when the limit value is reached (3.17 and 3.18).

The following points are negligible:

- The horizontal alignment of the pendulum for measurement of the mass of the pendulum is irrelevant. The relatively high limit values specified in the standard can be reached without any problems.
- The angle of striker has no significant influence on the result (3.11).
- The deviation from the free hanging position of the pendulum is negligible (3.5).
- If the line of contact of the striker to test piece is not perpendicular, this influence is very small. Even if the striker is tilted by 2° (maximum value), this only causes a change of 0.2 J (3.12).

At these points it could be possible to expand the frequency of verification from 1 year to probably 5 years.

7 | FURTHER ACTIVITIES

It is planned to publish this expanded measurement uncertainty concept for the calibration of Charpy pendulum impact machines as a national standard (as a DKD guideline). So, it would be for the public and especially for the calibration laboratories available. Accordingly, laboratories can adapt the calculation method to their own procedures and implement it in their accreditation.

The presentation of this approach to the responsible German standardization committee NA 062-01-44 AA „Schlagzähigkeitsprüfung für Metalle“ demonstrated high relevance and international significance. It was suggested that, following the German publication as a guideline, international publication as an ISO standard should be pursued.

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Endnotes

[1] 750 J Charpy pendulum impact machine according ISO 148-3, energy level 450 J, manufacturer ZwickRoell, site of installation IfEP Marl, radius of striking edge 2 mm, digital indication.

[2] To conduct the tests, an inclined force was applied to the force gauge. A realistic angle of 0.25° was chosen for the inclination so simulate a bad alignment of the measuring setup. Measurement conditions for the

three variants: a) 1 kN force gauge HBM U1, class 1 according ISO 376, amplifier HBM DK 38, length of the stilt for application of forces 220 mm. b) 2 kN force gauge HBM U2B, class 1 according ISO 376, amplifier HBM DK 38, length of the stilt for application of forces 40 mm. c) 1 kN force gauge HBM U1, amplifier HBM DK 38, via wire rope and eye, tilt of the hanging force measuring device compensated by counterweight. Conducting the tests under laboratory conditions with a granite table as base for force gauge and with a temperate of 20° ± 1°C.

[3] 300 J Charpy pendulum impact machine according ISO 148-2, manufacturer Roell + Korthaus Amsler, type RKP 300, year of construction 1985, site of installation MPA Stuttgart, radius of striking edge 2 mm, analogue display.

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