Identification of Characteristic Values in Impulse-Based Processes Using Small Specimens

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Abstract
Suitable approaches are needed for rapid and cost-efficient materials development. High-throughput experimentation reduces the identification time of suitable material compositions. One approach is to use small specimen geometries to save additional production costs. Hence, research is continuously being conducted on a new hardness test based on laser-induced shock waves. Thus far, characteristic values from the induced indentations have been extracted, which correlate with hardness and tensile strength. However, the indentation result varies in dependence of the specimen size and mass. This condition hinders the correlation between characteristic values and material properties. Thus, the goal was to induce similar indentation results to minimum specimen size. Herein, different mounting materials and methods were investigated. The created indentations were compared with those induced in large specimens. Essential mounting parameters were derived from the findings. Consequently, small specimens can be used for material characterization by considering these mounting parameters.

Keywords Mounting · Stiffness · Coefficient of restitution · Forming efficiency · Measuring instrument · TEA-CO₂ laser

1 Introduction
Materials development still depends on experimental testing techniques despite the availability of numerical-based modeling for many years [1], and the prediction of material behavior is even possible at the atomic level (e.g., by molecular dynamics) [2]. However, precise simulations are unlikely to solve all the problems of sound physical reasoning [3], particularly considering the transferability of simulation results. Simulations are helpful for materials development, but their results must be validated by experimental testing.

Experimental testing is time-consuming and costly. As resources are limited, the most promising experiments must be preselected considering the expected outcome. However, this procedure is based on experience and intuition. Moreover, the ability to design experiments becomes difficult with the increasing complexity of material compositions [4]. Therefore, the potential of non-intuitive parameter choices is disregarded [5].

One disadvantage of conventional material characterization techniques is that most of them are laborious and predict only a limited amount of material properties. Another disadvantage is that they require a standardized specimen geometry. Several techniques are needed to determine a variety of material properties when different material compositions are comprehensively characterized, thus leading to excessive costs. Hence, cost-efficient material characterization techniques are necessary to meet the demands of efficient material composition identification with a specific performance profile [6]. A novel approach is to perform high-throughput experiments on small specimens with simple geometry to overcome resource limitations and introduce new frontiers for experimental materials development [7]. Therefore, suitable characterization techniques must be identified that can identify a wide range of conventional material properties and rapidly test the aforementioned specimens.

The characteristics of a novel hardness testing technique based on TEA-CO₂ laser-induced shock waves are investigated in this paper [8]. Laser systems are highly dynamic compared with mechanical ones [9]. Shock waves can be created at high cycle rates due to the high repetition rate of lasers, thus making them suitable to penetrate the indenters in the material with high-throughput. Another advantage of the TEA-CO₂ laser-specific wavelength of $\lambda = 10.6 \mu m$ lies...
in its creation of a quasi-instant plasma with a high-intensity laser beam ($> 10^8$ W/cm$^2$), which absorbs nearly all the irradiation [10]. Thus, no ablation is observed on metals and technical ceramics compared with other laser shock peening processes with short wavelengths [11]. Therefore, pre-treatment and ablation layers are unnecessary for TEA-CO$_2$ laser-induced shock waves [12].

A shock wave is induced above a spherical indenter with the TEA-CO$_2$ laser, which pushes it inside a specimen. The penetration of the indenter creates an indentation in the specimen. Up to 90 indentations per minute can be created reproducibly with this procedure [13]. Characteristic values are extracted from the indentation geometry, which correlates with mechanic material properties. This laser-based technique is hereinafter referred to as LiSE. Thus far, the indentation depth, pile-up height, and indentation diameter of the extracted characteristic values strongly correlate with the Vickers hardness [14] and tensile strength [15]. Neural networks can be used to connect the characteristic values with material properties [16].

The indentation behavior of LiSE is comparable to drop tests [17]. In impact-based forming processes, a reduction of the specimen mass at a constant mass of the collision partner leads to a low forming energy efficiency $\eta_f$ [18]. This phenomenon hinders the correlation with different material properties without determining the material behavior in accordance with the specimen size.

The main characteristics of a collision include a short contact time and high stresses that develop in the center of the contact area between the two collision partners [19]. The available forming energy for such impacts is among heat and friction losses described by the forming energy efficiency $\eta_s$. The forming energy efficiency $\eta_s$ depends on the masses of the collision partners (here: mass of the indenter $m_i$ and effective mass of the counterpart $m_{el}$) and the coefficient of restitution (COR) $u$ [18].

$$\eta_s = \frac{(1 - u)^2}{1 + \frac{m_i}{m_{el}}}.$$  

(1)

The literature indicates that a mass ratio of $m_i / m_{el} < 0.1$ is usually reported for good forming energy efficiency [20]. Many existing predictions describe the COR and the elasto-plastic contact mechanics [21]. The challenge in understanding the COR lies in the influence on the impact behavior by many factors, such as the material combination, the shape of the indenter, the relative impact velocity, and the induced stress field [22].

The thickness of the specimen in relation to the indenter diameter represents another influence on the COR. Søndergaard et al. revealed that the COR decreases at constant indenter diameter $D_i$ with increasing specimen thickness $h_p$ up to a critical ratio [23]. Patil et al. additionally obtained that a critical ratio of $h_p/D_i > 2$ results in a constant COR considering the impact between a spherical indenter and plate regardless of the metal [24]. They explained this effect using two mechanisms. First, energy dissipated into flexural vibrations, which decrease the COR [25]. Second, the generation of elastic waves during the impact is reflected on the underside of the specimen and propagates back to the penetrating indenter [25]. These waves can influence the penetration of the indenter depending on the thickness $h_p$ of the specimen. The propagation velocity $v_{el}$ of these elastic waves depends on Young’s modulus $E_p$ and the density $\rho_p$ of the specimen material [26]:

$$v_{el} = \sqrt{\frac{E_p}{\rho_p}}.$$  

(2)

Furthermore, Søndergaard et al. revealed the importance of a mounting system for the plates [23]. They demonstrated that if minimal support is provided by the mounting system, then an increasing amount of kinetic energy is transferred to the kinetic energy of the plate [23], leading to a low COR [25].

Two parameters are derived for LiSE based on the literature, which could lead to similar indentation results in smaller specimen sizes compared with large and heavy specimens. The two parameters are the mass ratio between the collision partners [20] and the stiffness of the mounting system [23]. Søndergaard et al. have already revealed the effect of mounting system on plate support; different mounting materials and methods were investigated to understand effectively the interaction between small specimens and mounting systems as well as their influence on the indentation result. The created indentations were compared with those induced in large and heavy reference specimens. It is hypothesized that the indentation result will not be significantly influenced compared with that of the reference specimen:

1. when the mass of the effective mounting system is sufficiently large in relation to the indenter mass;
2. when the stiffness of the effective mounting system is sufficiently large in relation to the applied maximum force.

2 Materials and Methods

2.1 Laser process

The experiments are conducted with a TEA-CO$_2$ laser. The pulse energy is emitted with a wavelength of $\lambda = 10.6$ μm with a pulse duration of $t_p = 100$ ns. The pulse duration refers to the full width at half maximum [17]. The beam quality factor is $M^2 = 28.4$, and the spatial energy distribution
is best approximated as homogeneous (flat top). Pulse energies $E_p$ between 4.5 J and 5.0 J were used. The laser beam was focused on a target via a concave focusing mirror with a focal length $f = 200$ mm, resulting in a focus area of $A_F = 4$ mm$^2$. The indentations were created with spherical indenters with a suitable indenter diameter of $D_I = 3$ mm according to [17]. The properties and masses of the investigated indenters are listed in Table 1.

A cylindrical pressure cell made of brass was used to increase the acting shock wave pressure on the indenter (Fig. 1). Findings by Corsi et al. suggest that the reflected shock wave front can move fast in cylindrical cavities through the heated air of the preceding unreflected shock wave [29]. This phenomenon leads to a superposition of the preceding and the reflecting shock waves, which increases the acting shock wave pressure. The cylindrical pressure cell has a height of 10 mm and an inner diameter of 3.02 mm. The pressure cell also acts as a guideway for the indenter due to its placement inside the pressure cell. The specimens are clamped on a mounting plate made of aluminum with a thickness of $h_P = 10$ mm.

### 2.2 Force Measurement

Force measurements were performed with piezoelectric polyvinylidene fluoride (PVDF) shock gauge sensor from Piezotech (piezo strain constant of 22.0 pC/N). The sensor is embedded in polytetrafluoroethylene (PTFE) foil and has additional polyester protection on both sides (sensor model S_25CP). The PVDF sensors have a nanosecond resolution and are suitable for recording measurements with impact loading [30]. Figure 2 shows that the PVDF sensor was fixated on a ceramic blank.

| Material                      | Density   | Young’s modulus | Indenter mass |
|-------------------------------|-----------|-----------------|---------------|
| Aluminum oxide (purity 99.2%)| 3.95 g/cm$^3$ | 390 GPa         | 0.056 g       |
| Bearing steel 100Cr6         | 7.85 g/cm$^3$ | 210 GPa         | 0.111 g       |
PVDF sensors have a nanosecond resolution and are suitable for recording measurements with impact loading. The sensing area of 1 mm² was positioned directly below the indenter. The measurement repeatability of the sensor is approximately 1% of the measured value. An Al99.5 foil (thickness of 50 µm) was placed between the indenter and the PVDF sensor to protect the sensor from laser irradiation. A pressure cell was used as a hold-down device to guarantee contact without an air gap between the foil and sensor. The signal from the PVDF sensor was fed into a charge amplifier from Kistler (type 5015A). The measurement repeatability of the charge amplifier is less than 0.5% of the measured value. The charge amplifier was connected to a LeCroy Waverunner LT374 oscilloscope to gain a time-resolved force measurement. The force signal fluctuates ± 0.3 N from 0 when measuring an empty signal with no pressure on the sensor. The validation of the force measurement method is described in [31], which indicates that the measurement error is below 1.0 N for the measurement method.

The maximum force and transferred momentum were measured from each force–time profile. The transferred momentum from the shock wave on the indenter is independent of the investigated indenter material [13, 32]. The transferred momentum is determined by the integration of the force–time curve (as shown in Fig. 3) up to the maximum force. The maximum impact velocity v₀ is derived from the transferred momentum M and the mass of the indenter mᵢ,

\[ v₀ = \frac{M}{mᵢ}. \]

The shape of the impulse is ideal. Therefore, the following applies to the initial conditions.

\[ s(t = 0) = 0, \quad v(t = 0) = v₀, \]

where s is the indentation depth and v is the velocity. The maximum force \( F_{max} \) is derived by solving the equation of motion according to [33] with the initial conditions from Eq. (4).

\[ F_{max} = \left( \frac{125}{72} \cdot m₁^3 \cdot v₀^6 \cdot D_I \cdot E^2 \right)^{1/5}. \]  

The effective Young’s modulus \( E^* \) is calculated in accordance with [34] using the material properties of the penetrated material (Sect. 2.4.1). Young’s modulus is \( E = 210,000 \) N/mm² for the investigated steel and \( E = 70,000 \) N/mm² for the investigated aluminum [35]. The Poisson’s ratio is \( \nu = 0.27 \) and \( \nu = 0.34 \) for steel and aluminum, respectively [35].

\[ E^* = \frac{E}{1 - \nu^2}. \]

The indenter diameter and laser parameters, such as the pulse energy, were kept constant for the experiments. The impact velocity \( v₀ \) and the maximum force \( F_{max} \) of the indenter only change depending on the investigated indenter masses \( mᵢ \) (Table 1) and the material properties of the penetrated materials (Sect. 2.4.1).

2.3 Conventional Hardness Measurement

Brinell hardness was determined using a DuraScan 50 G5 hardness tester from Struers. A test force of 24.52 N was used for the Brinell hardness tests to penetrate a tungsten carbide indenter with a diameter of 1 mm in the material for 10 s [36].

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2.4 Mounting

2.4.1 Specimen Masses

Specimens of different sizes and masses made of Al99.5 and S235 were investigated, and these specimens are summarized in Table 2. The masses were measured with an AUW120D analytical balance from Shimadzu, and the measurement repeatability is ± 1·10^{-4} g. Additionally, reference specimens were used. Their masses were at least 40 times larger than the indenter masses (Table 1) to avoid any considerable influences of mass ratio between indenters and specimens on the indentation result according to recent findings [20]. The aluminum specimens have dimensions of 22.0 mm × 22.0 mm × 3.7 mm ($m_{\text{ref}} = 4.9$ g) after polishing, and the steel specimens made of S235 have dimensions of 22.0 mm × 22.0 mm × 4.8 mm ($m_{\text{ref}} = 18.3$ g). In addition, other reference specimens of S235 are used, with dimensions of 29.9 mm × 30.0 mm × 29.1 mm ($m_{\text{ref}} = 204.9$ g). Moreover, EN AW-6082 T6 specimens were investigated with the dimensions of 22.0 mm × 22.0 mm × 4.7 mm ($m = 6.1$ g).

2.4.2 Mounting materials

2.4.2.1 Material Properties

The small specimens described in Sect. 2.4.1 were mounted in different resins and metals. The density and Young’s modulus of the mounting materials varied to identify their influence on indentation in small specimen masses. The principal differences between the metal and resin-based mounting systems are shown in Fig. 4. The different material properties of the mounting materials are listed in Table 3. The listed resin-based mounting materials are usually utilized when mounting metals for metallography purposes, and their Young’s modulus may vary in accordance with the mounting procedure. Therefore, Young’s modulus was determined for the prepared resin mounts according to [37] with a Zwick/Roell Z250 testing machine. The Poisson's ratio of the mounting materials is $\nu = 0.30$ according to [38].

The small specimens in the metal mounting system were inserted in round blind holes, which were created by milling. The diameter of the blind holes corresponds to the diagonal of the contact surface of small specimens (Fig. 4). The height of the small specimens was 100 µm higher than the maximum depth of the milled blind holes. The small specimens were pressed into the metal mounting system and laterally fixed with a LevoCit, a fast-curing resin. All the specimens were polished after mounting in the mounting systems.

2.4.2.2 Definition of Parameters to Describe the Influence of the Mounting System on the Indentation Result

Two parameters are defined herein, namely the effective mass ratio and the absolute elastic longitudinal strain $e_{\text{eff}}$ of the effective mounting system, to describe the influences on the indentation result. The effective mass ratio is the quotient of the mass of the indenter $m_I$ and the mass of the effective mounting system $m_{\text{eff}}$. The latter comprises the mass of the specimen $m_P$ and the effective mass $m_{\text{E}'}$ below the specimen. The resulting effective masses $m_{\text{E}'}$ are shown in Fig. 5.

\[ m_{\text{eff}} = m_P + m_{\text{E}'} \]

### Table 2 Masses of mounted specimens with varying specimen sizes of Al99.5 (specimen height $h = 2.9$ mm) and S235 ($h = 1.9$ mm) after polishing

| Specimen support area | Al99.5 | S235 |
|-----------------------|--------|------|
| 2.0 mm × 2.0 mm       | 0.028 ± 0.001 g | 0.047 ± 0.001 g |
| 2.5 mm × 2.5 mm       | 0.044 ± 0.001 g | 0.067 ± 0.001 g |
| 3.0 mm × 3.0 mm       | 0.066 ± 0.001 g | 0.102 ± 0.001 g |
| 5.0 mm × 5.0 mm       | 0.189 ± 0.001 g | 0.371 ± 0.001 g |

### Table 3 Material properties of the investigated mounting systems according to [38] and [39]

| Material     | Density  | Young’s modulus | Poisson’s ratio |
|--------------|----------|-----------------|-----------------|
| EpoFix       | 1.14 g/cm³ | 3469 N/mm²     | 0.30            |
| VersoCit-2   | 1.15 g/cm³ | 4185 N/mm²     | 0.30            |
| ClaroCit     | 1.14 g/cm³ | 4419 N/mm²     | 0.30            |
| DuroCit      | 1.57 g/cm³ | 5669 N/mm²     | 0.30            |
| EN AW-6082 T6| 2.70 g/cm³ | 70,000 N/mm²   | 0.34            |
| 1.4305       | 7.90 g/cm³ | 210,000 N/mm²  | 0.27            |
The absolute elastic longitudinal strain $\varepsilon_{\text{eff}}$ of the effective mounting system is described by the applied maximum force $F_{\text{max}}$, which is set in relation to the effective stiffness $K_{\text{eff}}$ of the effective mounting system and the height of the effective mounting system $h_{\text{E}}$.

$$\varepsilon_{\text{eff}} = \frac{F_{\text{max}}}{K_{\text{eff}} \cdot h_{\text{E}}}.$$  (8)

$$\frac{1}{K_{\text{eff}}} = \frac{h_1 \cdot (1 - \nu_1^2)}{E_1 \cdot A_p} + \frac{h_2 \cdot (1 - \nu_2^2)}{E_2 \cdot A_p} + \frac{h_3 \cdot (1 - \nu_3^2)}{E_3 \cdot A_p}.$$  (9)

$$\varepsilon_{\text{eff}} = \frac{F_{\text{max}}}{h_{\text{E}} \cdot A_p} \left[ \frac{h_1 \cdot (1 - \nu_1^2)}{E_1} + \frac{h_2 \cdot (1 - \nu_2^2)}{E_2} + \frac{h_3 \cdot (1 - \nu_3^2)}{E_3} \right].$$  (10)

The spring stiffness of the effective mounting system is calculated with the support area of the small specimen $A_p$, the height of the small specimen $h_1$, the height of the mounting system below the small specimen $h_2$, and the height of the support table $h_3$ and the effective Young’s modulus $E^*$, which comprise Young’s modulus and the Poisson’s ratio of the small specimen ($E_1, \nu_1$), the mounting material ($E_2, \nu_2$), and the support table ($E_3, \nu_3$). In the following, the mounting medium and the support table below the specimens are referred to as segments. The achieved effective stiffnesses $K_{\text{eff}}$ are shown in Fig. 6.

The contact time $t_c$ between the indenter and the specimen is limited to a short period due to the nature of the impact. Hence, only some segments are assumed to have an influence on the indentation process due to a short contact time depending on the height of the segment and the propagation speed of elastic waves (in the respective segment). The contact time $t_c$ between indenter and specimen was calculated in accordance with Hertzian contact theory. Hertzian contact theory can be used for elastic collisions to determine the contact time $t_c$ between the indenter and the specimen. The contact time depends on Young’s modulus and Poisson’s ratio of the indenter ($E_I, \nu_I$) and the specimen ($E_P, \nu_P$), as well as the maximum impact velocity $v_0$, the indenter diameter $D_I$, and the density of the indenter $\rho_I$ [25]:
The propagation time of the elastic wave was calculated by dividing the distance traveled in the direction of the normalized surface by the elastic wave propagation speed of the respective segment. The material-specific propagation velocity for each segment is derived in accordance with Eq. (2), and the material properties are listed in Table 3. Figure 7 shows the contact times for the two investigated specimen materials and the duration of elastic wave propagation for each tested combination. Figure 7 shows only the minimum propagation time for the four differently tested plastic-based mounting systems.

All the segments that lie within the contact time are considered for calculating the effective mass and spring stiffness of the effective mounting system. The propagation velocity of the elastic wave is substantially slower compared to the propagation velocity in the metals in the

\[ t_c = 3.21 \cdot \left[ (1 - v_1^2) + (1 - v_p^2) \cdot \frac{E_1}{E_p} \right]^{2/5} \cdot \frac{D_1}{2 \cdot \left( \frac{E_1}{\rho_1} \right)^{2/5}} \cdot \frac{1}{v_0^{1/5}}. \]

(11)

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resin-based mounting systems. Therefore, the support table has no influence on the indentation process. Figure 8 shows the two different scenarios derived from Fig. 7 for the tested combinations.

2.4.3 Specimen Width

The spacing on small specimens becomes difficult, whereas the indentations can be easily spaced on bulk materials [40]. Minimum distances in quasistatic hardness testing are defined between two indentations and between an indentation and the specimen edge. The minimum distance to the specimen edge must be 2.5 times the mean indentation diameter from the center of the indentation, according to Brinell hardness testing [36]. Hence, the extent to which these distance specifications between an indentation and the edge apply to impulse-based indentation processes was investigated. Indentations were created at different distances to the edge to derive a minimum width between edge and indentation for the small specimens. A trend line of the indentation diameter was derived from the created indentations. The trend line is a logarithm function describing the average indentation diameter based on the edge distance.

The distance at which the derived trend line deviated significantly from the indentation result created at a sufficiently large distance from the edge was considered as the minimum distance between indentation and specimen edge. Indentations with a sufficiently large distance were created at a distance of at least five times the indentation diameter from the specimen edge.

Herein, the standard deviation was used and was defined to be significant when the trend line is outside the dispersion...
range of the indentations that were created at large distances from the edge. The mean value and standard deviation of the indentation diameter, created at a sufficiently large distance from the edge, were determined from ten indentations.

### 3 Results

#### 3.1 Influence of Mounting System on Indentation Result

Figure 9 shows the results of the conventional Brinell hardness measurement based on the specimen mass and mounting system. No significant influence on hardness is obtained between the different specimen masses.

Figure 10 shows the indentation results as false color images based on the specimen mass for Al99.5 and S235. The specimens in the mounting system are embedded in DuroCit, except for the respective heaviest specimens. Thus, the indentation increases for large specimen masses.

Figure 11 shows the indentation diameter, and Fig. 12 reveals the indentation depth plotted against the absolute elastic longitudinal strain \( \varepsilon_{\text{eff}} \) of the effective mounting system. In both figures, the indentation diameter and depth decrease as the absolute elastic longitudinal strain \( \varepsilon_{\text{eff}} \) increases.

Figure 13 shows the normalized indentation volume versus the absolute elastic longitudinal strain of the effective mounting system. The indentation volume was calculated with the indentation diameter and depth from Figs. 11 and 12, respectively. The indentation volume is divided by the maximum indentation volume of the respective macro specimens. A significant reduction in the normalized indentation volume is observed when the amount of absolute elastic longitudinal strain of the effective mounting system is \( \varepsilon_{\text{eff}} \geq 0.004\% \). Moreover, Fig. 14 shows the normalized indentation volume versus mass ratio. The determined effective mass ratio of \( m_{\text{eff}} / m_{I} > 20 \) shows no significant change in indentation volume.

Figure 15 shows that the measured characteristic values are converted to Brinell hardness values according to
The results indicate that converted Brinell hardness converges to the conventional obtained ones for large effective masses. However, the converted Al99.5 hardness values, which were obtained from large effective masses, are slightly lower than the conventional ones. By contrast, the values obtained on S235 are considerably larger than the conventional values. The high values obtained on S235 can be explained by the strain rate effect, which may lead to an increase in strength for certain materials. Low carbon steels,
such as S235, are generally more sensitive to high strain rates compared with most other metals [41].

### 3.2 Determination of Minimum Specimen Width

Figure 16 shows the influence of the edge distance on the indentation diameter. A significant change from the standard deviation determined at a sufficiently large distance is observed starting at an edge distance $l_r = 885 \, \mu m$ from the center of the indentation based on the determined trend line. The coefficient of determination of the trend line is $R^2 = 0.22$, which is predominantly due to the increase in dispersion at small distances from the specimen edge. This finding corresponds to 3.1 times the value of the mean indentation diameter.

### 4 Discussion

The indentation behavior of LiSE is comparable to drop tests, which affects the indentation result based on the collision partners. Figure 10 demonstrates that a large effective mass of the specimen leads to large indentation geometries. Accordingly, the converted hardness (Fig. 15) is affected by the effective mass of the specimen during impact testing. By contrast, the hardness is unaffected by the effective mass of the specimens for conventional hardness testing (Fig. 9). The Brinell hardness remains constant based on the effective mass. However, a disadvantage of conventional indentation techniques lies in the considerably slower indentation process compared with LiSE. Thus far, up to 90 indentations per minute can be created reproducibly with LiSE [13]. Other indentation techniques, such as high-throughput nanoindentation, which can induce up to 200 indentations per minute, still exist [42]. These indentation rates are achieved by low spacing distances between two indentations. The spacing distance is less than 1 \, \mu m smaller compared with LiSE with approximately 2 mm.

Nanoindentation testing needs additional preparation efforts because the indentation depth should be at least 20 times larger than the arithmetic mean roughness $Ra$ [43]. Fulfilling these requirements for tested specimens (e.g., by LiSE) is easy because the indentation depths are on the microscale (Fig. 10). The size of the LiSE-induced indentations is comparable with microhardness testing because it is in the microscale range [44], whereas the maximum forces (Fig. 3) are in the range of conventional macroscale hardness tests [44]. Thus, the strong correlations between the characteristic values obtained by LiSE and the hardness obtained by Brinell on large reference samples explained the similarity of the procedures and acting forces [13]. The objective was to derive a suitable mounting system and minimum specimen size for the testing technique to ensure that these characteristic values determined on small specimens are still convertible to hardness and tensile strength [13].

When performing impact tests, such as LiSE [17], Søndergaard et al. already found that the indentation result can be described as a function of the ratio of specimen thickness to indenter diameter via the contact time and the propagation velocity of elastic waves [23]. Only some segments underneath the specimen have an influence on the indentation process when the contact time during the indentation is too short. By contrast, if a wrong contact time was determined, then the respective effective mass $m_{eff}$ (Eq. 7) and absolute elastic longitudinal strain $e_{eff}$ (Eq. 10) would have resulted in either large or low values. However, the results in Figs. 13 and 14 reveal a good fit with the expected course when determining the effective mass and absolute elastic longitudinal strain according to the contact time in Fig. 7. Thus, the results in Figs. 13 and 14 emphasize that the contact time between the indenter and the specimen and the propagation velocity of elastic waves must be considered when designing the mounting system. Accordingly,
the effective mass and stiffness of the mounting system are affected by the indentation time.

However, if the indented specimens are too thin, then elastic waves reflected from the interfaces can counteract the indentation movement of the indenter [23]. The indentation time in the experiments based on Eq. (11) was larger than that of the elastic waves needed to travel through the thin specimens and counteract the indenter movement (derived from Eq. (11) and shown in Fig. 7). Therefore, the penetration of the indenter should be affected by the reflected elastic waves. For this purpose, Patil et al. already demonstrated experimentally that only a critical ratio independent of the metals of $h_p/D_i > 2$ is needed to avoid affecting the COR significantly [24]. However, their derived critical specimen thickness is two times smaller than the critical thickness, which can be derived from Hertzian contact theory and the propagation speed of elastic waves. Moreover, Patil et al. ascribed the dominant effect of energy dissipation when using small plates to the flexural vibrations and not to the elastic waves [25]. The LiSE experiments also reveal that indentation results can be created in thin specimens that are not significantly different from those of the reference specimens despite using thinner specimens $h_p$ (two-thirds of the indenter diameter $D_i$) in comparison to Patil et al. [25]. The difference between the results from Patil et al. and Sondergaard et al. and those presented in this paper lies in the embedded systems in different mounting systems. Thus, the mounting systems should hinder these flexural vibrations, which also minimizes the loss of energy dissipation. However, the process is limited to substantially thin specimens based on the maximum acting forces. These effects are already described for quasistatic hardness testing techniques [34]. A series of experiments is prepared with varying specimen thickness to clarify the aforementioned finding for LiSE.

The following requirements for the mounting system are derived from the experiments. Therefore, the indentation results can be created in thin specimens that are not significantly different from those of the reference specimens. First, the mounting system must experience an absolute elastic longitudinal strain $e_{eff} < 0.004\%$ (Fig. 13). Second, the effective mass in relation to the indenter mass is $m_{eff}/m_I > 20$ (Fig. 14). This mass ratio, wherein no significant change in indentation volume occurs, is within the range specified in the literature for drop forging as a suitable mass ratio for low energy dissipation [19].

However, deviations from the expected course are still observed on the smallest aluminum specimens in Fig. 14 (2 mm × 2 mm, cf. Table 2). The normalized indentation volumes for the smallest specimens are above the expected value. This finding can be explained by the influence of the distance of the indentation from the edge. Figure 16 shows that the penetrating indenter experiences a low mechanical resistance associated with a low section modulus when the indentations are too close to the edge. Consequently, the indentation diameter increases. The minimum width for the smallest specimens can be derived on the basis of the experimental findings. Approximately three times the distance of the mean indentation diameter must be maintained to avoid significant influences on the indentation geometry. This value is comparable to the distances provided in [36] for conventional indentation tests.

## 5 Conclusions

The following conclusions are drawn on the basis of the conducted experiments.

- If the following requirements are met, indentation results can be achieved in small specimens that do not differ significantly from those of reference specimens, which are considerably large and heavy.
  - The mass ratio between the effective mass (mass of the specimen and effective mass of the mounting system below the specimen) and the indenter mass must be larger than 20.
  - The effective mounting system must not exceed an absolute elastic longitudinal strain of 0.004\%.
  - Similar to quasistatic hardness testing, limitations are expected for thin specimens based on the applied force. This effect will be further investigated for impact testing. No influence was obtained herein for specimen thicknesses above 2/3 of the indenter diameter.
- Consequently, small, and simple specimens can be used for impact-based materials characterization, which fosters the development of resource-saving materials.

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**Declarations**

**Conflict of Interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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