

ASTM D5946 ASTM D7334 ASTM D7490 ISO 27448

optische Kontaktwinkelmessung und Tropfenkonturanalyse zur Bestimmung von Oberflächenenergie sowie Grenz- und Oberlfächenspannung

ASTM D1331 ASTM D1417 ISO 1409

kraftbasierte Tensiometrie, dynamische Kontaktwinkelmessung und Bestimmung der Adhäsionskraft





optische Stabilitätsund Alterungsanalyse mehrphasiger Dispersionen



Zeta-Potential-Messung auf Fasern, Pulvern und plattenförmigen Festkörpern



Vielseitige Laboranalysegeräte für die umfangreiche Charakterisierung von Materialoberflächen und der Wechselwirkungen zwischen Werkstoffen.

## Mehr erfahren >



DataPhysics Instruments GmbH Raiffeisenstraße 34 • 70794 Filderstadt, Deutschland Telefon +49 (0)711 770556-0 • Fax +49 (0)711 770556-99 sales@dataphysics-instruments.com www.dataphysics-instruments.com DOI: 10.1002/mawe.202200283

#### ARTICLE

### Modelling and simulation of the hardness profile and its effect on the stress-strain behaviour of punched electrical steel sheets

Modellierung und Simulation des Härteprofils und dessen Einfluss auf das Spannungs-Dehnungs-Verhalten gestanzter Elektrobleche

# P. Kubaschinski<sup>1</sup> | A. Gottwalt-Baruth<sup>1</sup> | U. Tetzlaff<sup>1</sup> | H. Altenbach<sup>2</sup> | M. Waltz<sup>1</sup>

<sup>1</sup>Technische Hochschule Ingolstadt, Kompetenzfeld Werkstoff- und Oberflächentechnik, Ingolstadt, Germany

<sup>2</sup>Otto-von-Guericke-Universität Magdeburg, Institut für Mechanik, Magdeburg, Germany

#### Correspondence

P. Kubaschinski, Technische Hochschule Ingolstadt, Kompetenzfeld Werkstoffund Oberflächentechnik, Ingolstadt, Germany. Email: Paul.Kubaschinski@thi.de

**Funding information** Federal Ministry of Education and Research (BMBF); Audi AG

#### Abstract

The shear cutting of electrical steel sheets has a significant influence on the magnetic and mechanical material properties. Due to plastic deformation and strain hardening in the area of the punched edge, the electrical steel sheets exhibit a characteristic hardness profile. This study deals with the modelling of the resulting hardness profile by means of finite-element simulations. Elastic-plastic material properties are obtained from spherical nanoindentation testing as a function of the local hardness. In particular, representative stress-strain values are determined by applying Tabor's concept of indentation stress-strain curves. The choice of the appropriate stress- and strain-constraint factors is discussed with respect to the nanoindentation test setup used. Following this, the representative stress-strain values are analytically described to determine true stressstrain curves for the local assignment of different material models depending on the hardness. The implementation of the modelling approach in a finite-element simulation is presented for a punched electrical steel sheet specimen under monotonic loading. The simulation results are basically in good agreement with experimental data and confirm the expected influence on the mechanical material behaviour due to the shear cutting process.

#### **KEYWORDS**

electrical steel, hardness distribution, material modelling, nanoindentation, punched edge

#### Abstract

Scherschneiden hat einen wesentlichen Einfluss auf die magnetischen und mechanischen Werkstoffeigenschaften von Elektroblech. Aufgrund

This is an open access article under the terms of the Creative Commons Attribution Non-Commercial NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made. © 2023 The Authors. *Materialwiss. Werkstofftech.* published by Wiley-VCH GmbH.

#### - WILEY VCH

513

plastischer Verformung und Kaltverfestigung im Bereich der Stanzkante weisen Elektroblechschnitte ein charakteristisches Härteprofil auf. Dieses wird in der vorliegenden Arbeit im Rahmen von Finite-Elemente-Simulationen modelliert. Elastisch-plastische Materialeigenschaften werden durch Nanoindentierung mit kugelförmigem Prüfkörper als Funktion der lokalen Härte ermittelt. Dabei handelt es sich um repräsentative Spannungs-Dehnungs-Werte, die sich mithilfe Tabors Konzept aus dem Eindruckversuch bestimmen lassen. Die Wahl geeigneter Spannungs- und Dehnungsproportionalitätsfaktoren wird unter Berücksichtigung des verwendeten Prüfaufbaus diskutiert. Im Anschluss daran erfolgt die analytische Beschreibung der repräsentativen Spannungs-Dehnungs-Werte zur Bestimmung wahrer Spannungs-Dehnungs-Kurven, die basierend auf dem zugehörigen Härtewert zur Zuweisung lokal unterschiedlicher Materialmodelle herangezogen werden. Die Umsetzung des Modellierungsansatzes geschieht für eine gestanzte Elektroblechprobe unter monotoner Beanspruchung. Der Vergleich der Simulationsergebnisse mit experimentellen Daten zeigt grundsätzlich eine gute Übereinstimmung und bestätigt den erwarteten Einfluss des Scherschneidens auf das mechanische Werkstoffverhalten.

SCHLÜSSELWÖRTER

Elektroblech, Härteverteilung, Materialmodellierung, Nanoindentierung, Stanzkante

#### 1 | INTRODUCTION

The rotor and stator of electric drives consist of stacked electrical steel sheets, which are typically manufactured in a shear cutting process for large-scale production. Shear cutting causes substantial strain hardening and residual stresses as well as an increase of the surface roughness in the area of the punched edges. Due to that, not only the magnetic, but also the mechanical properties of the material are affected by the punched edges of the complex rotor and stator geometrical shapes [1, 2].

The mechanical strength of the punched electrical steel sheets is diminished, which makes it necessary to consider the impact of shear cutting in the dimensioning of the components. In the context of an analytical fatigue life assessment, the influence of manufacturing is usually estimated by reduction factors to reduce the theoretical strength of the material [3]. In this study, an alternative approach is presented, considering the impact of shear cutting during material modelling for numerical simulations.

The elastic-plastic material model accounts for the induced plastic deformation and strain hardening of the punched electrical steel sheet by locally adjusting the material properties depending on its hardness profile. For this purpose, information about the resulting hardness profile of the punched electrical steel sheet and the relation with the elastic-plastic material properties are required. During instrumented indentation testing, the load-displacement curve of a spherical indenter is continuously recorded, which can then be related to the local true stress-strain curve of the material.

The present work aims to give an overview of the basics of instrumented nanoindentation testing, including the mathematical relations between hardness and true stress-strain curve of metals according to Tabor [4]. Spherical nanoindentation tests are performed on a punched electrical steel sheet specimen to provide the parameters for the calculation of representative stressstrain values. After the processing of the experimental data, a finite-element modelling approach is developed, which enables the local assignment of the varying material behaviour in the area of the punched edge.

In a final step, the modelling approach is implemented in Abaqus, performing numerical simulations of the punched electrical steel sheet specimen under monotonic loading. The resulting material behaviour and influence of the punched edge on the stress response are evaluated and compared with existing experimental data. Thus, it can be assessed whether the material model considers the impact of the punched edge in a sufficient way.

#### 2 | THEORETICAL BACKGROUND

### 2.1 | Basics of instrumented indentation tests

Indentation tests have been a common procedure to characterise the mechanical properties and measure technological characteristics of engineering materials for more than a century [4–6]. In comparison with destructive testing methods, indentation tests can be advantageous, since they are simple to perform, low-cost and can be applied on in-service components as well as small material samples. A hard indenter of a certain geometry is pushed into the material to be tested by applying a specified load or displacement. The geometric dimensions of the residual indentation on the surface of the sample are measured and correlated to the hardness of the material. Several empirical formulations have been derived for specific material classes with the aim of correlating hardness and further mechanical properties such as yield and tensile strength [4, 6-12].

With the development of instrumented indentation testing, it became possible to continuously control and record the loading and displacement of the indenter on micro- or nanoscale [5, 6, 13]. Due to that, the capabilities of conventional indentation testing have been significantly extended, especially for the determination of elastic-plastic material properties. The recorded load-displacement (L-h) curve of the indenter depends on several testing parameters, however it is particularly related to the uniaxial stress-strain  $(\sigma - \varepsilon)$  curve of the investigated material. The description of the correlation between the *L*-*h* and  $\sigma$ - $\varepsilon$  curve is difficult due to the complexity of the deformation process in the indentation region and the related strong non-linearities. As a result, several analytical methods considering different indenter geometries have been developed over the years.

Basically, it is necessary to distinguish between spherical and sharp indenter geometries. Sharp indenters (e.g., Berkovich, Vickers) are designated as geometrically self-similar, since they induce a characteristic strain condition during indentation depending on the indenter angle [13–15]. As a result, information about only one particular point of the stress-strain curve is obtained. In contrast, spherical indenters allow for a continuous change of the induced strain, as the contact angle varies with increasing indentation depth (displacement). With the strain as a function of indentation depth, the elasticplastic material behaviour can be deduced in the form of the true stress-strain curve. The conversion of the loaddisplacement curve into the corresponding stress-strain curve can be performed by using either a direct or an indirect approach [6]. The latter refers to mathematical and numerical methods, in which finite-element models of the indentation test are verified by corresponding experimental data to identify a relation between indentation process and material properties [13, 16]. Reliable estimations, however, are difficult to achieve, since the realistic modelling of friction between the contact surfaces of indenter and specimen is difficult, which influences the strain evolution in the indentation region. Moreover, experimental features like the condition of the indenter tip or the specimen's surface roughness cannot be sufficiently considered. The uniqueness of the solution (correlation between *L*-*h* and  $\sigma$ - $\varepsilon$  curve) is also still under discussion.

Considering the direct approach, the material properties are directly determined from experimental indentation tests, which has the advantage of taking into account the actual experimental setup and boundary conditions [13]. In this context, Tabor introduced the concept of indentation stress-strain curves in a pioneering work by defining a representative strain and stress [4-6, 13-16]. Based on the findings of Meyer, who identified the relation between indentation load and the contact radius of a spherical indenter, Tabor established a physical description of the material deformation during the indentation process [4, 17]. Assuming a fully plastic regime, Tabor empirically correlated the L-h and  $\sigma$ - $\varepsilon$ curve of the material by introducing so-called stress- and strain-constraint factors. In general, most research works agree with the idea of Tabor's representative strain and stress. Nevertheless, further development in the field of indentation stress-strain curves and controversy regarding the choice of constraint factors has occurred. Various publications can be found, which extend the approach by analysing the effect of the indenter shape and discussing the choice of constraint factors [18–23]. An overview of respective research work can be viewed in the literature [6, 13, 15].

Despite ongoing research, there is no broad agreement on the representative strain and stress formulations and the exact choice of constraint factors [5, 13, 14]. Reliable mathematical relations between the *L*-*h* and  $\sigma$ - $\varepsilon$  curve is still under discussion, even though Tabor's relations are widely accepted. The interest on spherical indentation tests increases, particularly as the experimental data provides more information compared to sharp indentation tests [13]. Due to the mentioned disadvantages of numerical methods (indirect approach), in this research work, the elastic-plastic material properties are directly determined by spherical instrumented

.5214052, 2023, 4, Dov

elibrary.wiley.com/doi/10.1002/mawe.202200283 by Technische Hochschule Ingolstadt, Wiley Online Library on [09/08/2023]. See the Terms

ons) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons

indentation testing. The applied relations and parameters are presented in the following section.

### 2.2 | Relation between hardness and stress-strain curve of metals

The elastic modulus of the investigated material can be obtained by the *L*-*h* curve, which is recorded during the instrumented indentation test. For the analytical description, Hertz's theory on the frictionless elastic contact between two spherical surfaces is considered as fundamental framework [24, 25]. In a further work, Sneddon derived the relationship between load, indentation depth and contact area for a rigid indenter of arbitrary profile [18, 25, 26]. According to the Oliver-Pharr method, the analysis of the unloading data of the *L*-*h* curve provides information about the elastic contact stiffness *S* [5, 25, 27]:

$$S = \frac{\mathrm{d}L}{\mathrm{d}h} = \frac{2}{\sqrt{\pi}} E_\mathrm{r} \sqrt{A} \tag{1}$$

where  $E_r$  is the reduced elastic modulus and A is the projected area of the elastic contact. The elastic contact stiffness S can be interpreted as the initial slope of the unloading data at maximum indentation load, Figure 1. For the reduced elastic modulus  $E_r$ , the following relation with the elastic modulus and Poisson's ratio of



**FIGURE 1** Load-displacement curve with indicated elastic contact stiffness, representation according to [25].

**BILD 1** Last-Eindringtiefen-Kurve mit angedeuteter elastischer Kontaktsteifigkeit, Darstellung nach [25]. specimen (*E*,  $\nu$ ) and non-rigid indenter (*E*<sub>i</sub>,  $\nu$ <sub>i</sub>) applies [5, 25, 27]:

$$\frac{1}{E_{\rm r}} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_{\rm i}^2)}{E_{\rm i}}$$
(2)

When the elastic contact stiffness S is obtained from the *L*-*h* curve and the indenter contact area A is measured, Equation (1) can be solved for the reduced elastic modulus. With the known elastic modulus and Poisson's ratio of the indenter and an assumed Poisson's ratio of the specimen material, the elastic modulus can be calculated in accordance with Equation (2). The relationship is valid for various indenter geometries, e.g., spherical, cylindrical and pyramidal indenters [25].

Regarding the determination of the true stress-strain curve, Tabor's approach of representative strain and stress can be applied for spherical instrumented indentation tests. The mean pressure  $p_m$  in the indentation region in the fully plastic regime is assumed to be proportional to the representative stress  $\sigma_r$  [4, 13, 27, 28]:

$$\sigma_{\rm r} = \frac{p_{\rm m}}{\psi} = \frac{L}{\psi \pi a^2} \tag{3}$$

The mean pressure  $p_m$  is expressed by the ratio of indentation load *L* to indenter contact area, whereas the contact area of a spherical indenter is given by the contact radius *a*. The stress-constraint factor  $\psi$  can be interpreted as a proportionality factor, which links the three-dimensional stress state during indentation to a comparable uniaxial stress state of a tensile test [4, 13, 27]. The stress-constraint factor is typically defined as  $\psi = 3$ . The representative strain  $\varepsilon_r$  is described by the ratio of contact radius *a* to indenter radius *R* using the strain-constraint factor  $\beta$  [4, 13, 27]:

$$\varepsilon_{\rm r} = \beta \frac{a}{R} \tag{4}$$

According to Tabor's work, the strain-constraint factor is empirically set to  $\beta = 0.2$ . As mentioned before, the specified values of the constraint factors are generally accepted [13, 27]. Nevertheless, there has been further research on the physical interpretation of these values and the modelling of the representative strain and stress [23, 29]. With the consideration of sink-in and pile-up phenomena, the analytical accuracy of spherical indentation tests has been improved, since the representative strain and stress tive strain and stress values strongly depend on the proper determination of the contact depth [28, 29]. According to the Oliver-Pharr method, the indentation depth  $h_c$  can

be expressed by maximum displacement  $h_{\text{max}}$ , maximum load  $F_{\text{max}}$ , contact stiffness *S* and the indenter shape coefficient  $\omega = 0.75$  for spherical indenters [25, 27, 28]. Subsequently, the contact radius *a'* can be calculated:

$$h_{\rm c} = h_{\rm max} - \omega \frac{F_{\rm max}}{S} \tag{5}$$

$$a' = \sqrt{2Rh_{\rm c} - h_{\rm c}^2} \tag{6}$$

With increasing indentation depth, the material can sink in or pile up at the edge of the indenter, which results in a change of the contact area between specimen and indenter, Figure 2 [27, 28]. The amount of sink-in or pile-up depends on the strain-hardening exponent n of the investigated material. A dimensionless correction parameter has been developed to consider the impact on the contact radius a [27, 28, 30]:

$$a = \sqrt{c^2 a'^2} = \sqrt{\frac{5}{2} \frac{2 - n}{4 + n} \left(2Rh_c - h_c^2\right)}$$
(7)

During the instrumented indentation test, representative strain and stress values can be continuously recorded with increasing indentation depth. The obtained values are then analytically described by suitable strainhardening functions, which results in the true stressstrain curve to be determined. Often the two-parametric



**FIGURE 2** Parameters of spherical indentation including sink-in and pile-up phenomena, representation according to [21].

**BILD 2** Kenngrößen des Eindruckversuchs mit kugelförmigem Prüfkörper unter Berücksichtigung des Einsinkens und Aufwölbens des Materials, Darstellung nach [21]. Hollomon function is applied to the plastic regime. The elastic regime with stresses below the yield strength  $\sigma_y$  is described by Hooke's law [13–15, 28, 29, 31]:

$$\sigma(\varepsilon) = \begin{cases} E\varepsilon, \ \sigma < \sigma_{\rm y} \\ K\varepsilon^n, \ \sigma \ge \sigma_{\rm y} \end{cases}$$
(8)

Equation (8) is defined with the elastic modulus E, the strength coefficient K and the strain-hardening exponent n. For the description of the true stress-strain curve, modified versions of Hollomon's power law and other strain-hardening functions are used as well [6, 27, 32]. Alternative formulations include, among others, formulations according to Ludwik and Ramberg-Osgood [33, 34].

#### 3 | EXPERIMENTAL METHODS: SPHERICAL NANOINDENTATION TESTING

#### 3.1 | Material

The material in this study is a fully processed non-oriented electrical steel sheet with a nominal thickness of 270  $\mu$ m and the following composition (mass fraction): 3.32% silicone, 1.10% aluminium, 0.16% manganese, 0.01% carbon, 0.002% sulphur, 0.010% phosphorus, balance iron. Therefore, the material exhibits a ferritic microstructure containing small non-metallic inclusions. The average grain size is approximately 100  $\mu$ m as measured by electron backscatter diffraction (EBSD).

Monotonic material properties are determined by quasi-static uniaxial tensile tests at room temperature with a constant strain rate of  $2.5 \cdot 10^{-4} \text{ s}^{-1}$ , Table 1. The specimen geometry used is described in detail elsewhere [35]. Due to a slight rolling texture, strength values and young's modulus in the rolling direction are lower than in other orientations. Hence, the material is investigated exclusively in the rolling direction in this study. The material exhibits a small yield plateau with an average yield strength of 440 MPa. Under quasi-static loading, the material shows a limited amount of hardening, resulting in a comparatively flat stress-strain curve with an ultimate

 TABLE 1
 Monotonic material properties of the studied electrical steel sheets in rolling direction.

TABELLE 1	Monotone Werkstoffeigenschaften der untersuchten Elektrobleche in	Walzrichtung.
-----------	---	---------------

Elastic modulus E [GPa]	Poisson's ratio $\nu$ [-]	Yield strength $\sigma_y$ [MPa]	Ultimate tensile strength $\sigma_{\rm uts}$ [MPa]	Elongation at break $A_t$ [%]
181	0.27	440	549	15

517

tensile strength of 549 MPa and an elongation at break of 15%, Figure 3.

When the electrical steel sheets are processed by shear cutting, the sheet metal is first elastically and then plastically deformed by the cutting edges of the punching tool. The local deforming capability of the material is reached and it finally tears (shear zone) and breaks (fracture zone), Figure 4a. Thereby it causes substantial strain hardening, which affects both the mechanical and magnetic material properties. The intensity of the resulting impact strongly depends on the selected cutting parameters, mainly the cutting clearance and the tool wear state. In this study, a punching tool with a sharp edge (tool radius  $R < 5 \,\mu$ m) and a cutting clearance of 35  $\mu$ m is used, resulting in a comparably slight rollover zone and burr.



**FIGURE 3** Monotonic tensile stress-strain curve of the studied electrical steel sheets.

**BILD 3** Monotone Spannungs-Dehnungs-Kurve der untersuchten Elektrobleche unter Zugbeanspruchung.



**FIGURE 4** Optical images of the specimen's punched edge, a) top view, b) polished microsection showing indentation measuring grid.

**BILD 4** Aufnahme der Stanzkante der Elektroblechprobe, a) Draufsicht, b) poliertes Schliffbild mit Eindruck-Messraster.

#### 3.2 | Test setup

Hardness and local stress-strain data are determined with an indentation load of 10 mN using the triboindenter TI premier (Bruker, Minneapolis, United States of America), which is equipped with a spherical diamond tip with a tip radius of  $2 \mu m$ . The tip area function was calculated by indenting fused silica. To obtain a deformation-free sample surface, sample preparation is performed by polishing with conventional metallographic techniques up to polishing with fine diamond suspension, followed by 12 hours of vibration polishing with water-free suspension Etosil (QATM, Mammelzen, Germany). Since nanoindentation is a particularly sensitive measuring method, indentations made too close to the punched edge or in irregularities like non-metallic inclusion are excluded in the analysis. The distance between the indentations is 10 µm in the highly deformed zones close to the edge and 20 µm in the area of the less deformed base material, Figure 4b. At an indentation load of 10 mN, which corresponds to the maximum value of the used Triboindenter, the contact depth is approximately 200 nm.

#### 3.3 | Results

The instrumented indentation test is performed considering a representative edge condition along the cutting line of the electrical steel sheet specimen. The results are evaluated for every indentation according to the presented measuring grid, Figure 4b. As might be expected, the hardness distribution shows the highest values with  $H \sim 6.0$  GPa closest to the punched edge in the area of the fracture zone, Figure 5. The shear and rollover zone also exhibit increased hardness values due to the induced plastic deformation during the shear cutting process. However, the hardness distribution plot clearly shows that the extension of the plastic zone into the steel sheet is limited. After a distance of approximately 0.3 mm from the punched edge, the hardness tends towards values of  $H \sim 3.0$  GPa, which corresponds to the reference hardness of the (unaffected) base material. For every measuring point, not only the hardness, but also the L-h curves are obtained. With this information, the related elastic-plastic material properties can be determined for different hardness values taking into account the impact of shear cutting. In this study, L-h curves are analysed for 7 different hardness values, including the reference and maximum value of the underlying hardness profile: H = 3.0 GPa to 6.0 GPa in 0.5 GPa steps.

The elastic moduli can be calculated according to Equations (1) and (2) by evaluating the unloading segment of the *L*-*h* curves. Assuming a constant Poisson's ratio of 0.27, which is known from uniaxial tensile tests, the evolution of the elastic modulus is obtained with respect to the hardness, Figure 6. The elastic modulus



FIGURE 5 Representative hardness distribution of the investigated punched electrical steel sheet.

**BILD 5** Repräsentative Härteverteilung des gestanzten Elektroblechs.



**FIGURE 6** Evolution of the elastic modulus with respect to the hardness measured by nanoindentation.

**BILD 6** Verlauf des durch Nanoindentierung gemessenen Elastizitätsmoduls in Abhängigkeit der Härte.

corresponding to H = 3.0 GPa of the unaffected material is about 14% smaller compared to the elastic modulus determined by uniaxial tensile test. The difference can be explained by the fact that the elastic modulus measured by indentation represents a weighted average of a certain sample volume including its specific microstructure and grain orientations [36]. The three-dimensional stress state further includes the material's elastic behaviour in directions other than parallel to the loading direction [37]. Besides, shear cutting seems to have a limited influence on the elastic modulus, which shows the tendency to increase with increasing hardness. The elastic moduli measured for hardness values of 6.0 GPa exhibit a slight decline due to the proximity of the indents to the punched edge and the related impact on the stiffness. However, the evolution of the elastic modulus can be described by linear least-squares regression. On this basis, the elastic moduli are determined for the considered hardness values, Table 2. The increase of the elastic modulus with increasing hardness has also been reported in the literature, for example, for high-strength alloy steel regarding the effect of machining near the superficial layer [38, 39]. In a further study on unalloyed cast iron, nanoindentation testing was performed before and after pre-straining, illustrating a similar correlation between hardness and indentation modulus [40].

Representative stress-strain data pairs ( $\varepsilon_r$ ,  $\sigma_r$ ) are calculated according to Equations (3) and (4) using the information of the *L*-*h* curves until maximum indentation load. In order to take into account sink-in or pile-up phenomena, the adjusted contact radius is calculated using Equations (5) to (7). The required strain-hardening exponent *n* is can be estimated by applying an iterative method [23, 28]. Due to the fact that the strain-hardening exponent derived by indentation depends on the surface characteristics, the actual value is unknown. As initial value of the iteration, the strain-hardening exponent measured by uniaxial tensile test can be applied. By fitting Hollomon's law, Equation (8), to the obtained data pairs, the value is then recalculated.

Regarding Tabor's approach, the stress and strain constraint factors are assumed to coincide with the mentioned empirical values  $\psi = 3.0$  and  $\beta = 0.2$ . However, looking at the results for the reference hardness H=3.0 GPa, it becomes evident that the magnitude of the stress constraint factor is too small, Figure 7a. The

**TABLE 2** Elastic moduli with respect to the considered hardness values determined by linear least-squares regression.

TABELLE 2 Mittels linearer Kleinste-Quadrate-Regression ermittelte Elastizitätsmoduln in Bezug auf die betrachteten Härtewerte.

<b>E</b> <sub>H3.0</sub> [GPa]	<b>E</b> <sub>H3.5</sub> [GPa]	<b>E</b> <sub>H4.0</sub> [GPa]	<i>E</i> <sub>H4.5</sub> [GPa]	<b>E</b> <sub>H5.0</sub> [GPa]	<b>E</b> <sub>H5.5</sub> [GPa]	<b>E</b> <sub>H6.0</sub> [GPa]
156	162	169	176	183	190	197

519



**FIGURE 7** Determination of stress constraint factor  $\psi$ , a)  $\psi = 3$  according to Tabor, b) calculated evolution of  $\psi$  based on uniaxial tensile test.

**BILD** 7 Ermittlung des Spannungs-Proportionalitätsfaktors  $\psi$ , a)  $\psi = 3$  gemäß Tabor, b) berechneter Verlauf von  $\psi$  basierend auf uniaxialem Zugversuch.

representative stress-strain data pairs ( $\varepsilon_r$ ,  $\sigma_r$ ) clearly show higher stress values compared with the true  $\sigma$ - $\varepsilon$ curve of the unaffected material, which is determined by uniaxial tensile test. One possible explanation for the significant deviation is the so-called indentation size effect [9, 41, 42]. Based on experiments with different indenter tip sizes, smaller sphere radii result in higher hardness values due to dislocation-based mechanisms. The empirical stress constraint factor  $\psi = 3$  is related to indentation tests on the macroscale using indenters with sphere radii in the order of magnitude of several hundred micrometres. Since the instrumented indentation tests in this study are performed on the nanoscale with a sphere radius of  $2 \mu m$ , the stress constraint factor has to be adjusted to ensure a satisfactory estimation of the true  $\sigma$ - $\varepsilon$  curve [41].

In this context, the true  $\sigma$ - $\varepsilon$  curve from the uniaxial tensile test is analytically described by Hollomon's law [19]. The data pairs ( $\varepsilon_r$ ,  $\sigma_r$ ) obtained from the spherical indentation test can then be compared with corresponding values of the uniaxial tensile test. The stress constraint factor  $\psi$  is calculated as the proportionality factor between both values as a function of the representative strain  $\varepsilon_r$ , Figure 7b. It becomes apparent that the stress constraint factor is shifted to higher values due to indentation size effect. The evolution over the representative strain between 3% and 8% is approximately constant with a mean stress constraint factor of  $\psi = 5.9$ . Values outside the specified strain boundaries are not considered due to the increased scatter of the indentation test data, especially for small displacements and indentation depths, respectively.



FIGURE 8 Representative stress-strain data pairs for the different investigated hardness values.

**BILD 8** Repräsentative Spannungs-Dehnungs-Datenpaare für die unterschiedlichen betrachteten Härtewerte.

For the calculation of the representative strain  $\varepsilon_r$ , the choice of the strain constraint factor  $\beta = 0.2$  seems valid with respect to the applied test setup and investigated electrical steel. Tabor's definition of representative strain is in good agreement with the approach of Ahn and Kwon, which is also mentioned in the literature for  $\varepsilon_r < 20\%$  [23, 29]. After the verification of the constraint factors, the representative stress-strain data pairs are determined for the investigated hardness values, Figure 8. The adjusted stress constraint factor results now in a good alignment of the reference hardness H=3.0 GPa

and the true  $\sigma$ - $\varepsilon$  curve from the uniaxial tensile test. Apart from that, the plot shows a clear correlation between the magnitude of representative stress and the hardness of the electrical steel sheet. The representative stress continuously increases over the investigated range of hardness values. As a result, the electrical steel sheets exhibit the highest strength values close to the punched edge in the area of the fracture zone.

#### 4 | DEVELOPMENT OF FINITE-ELEMENT MODELLING APPROACH

### 4.1 | Processing of nanoindentation test data

The nanoindentation test results have to be processed for the subsequent input in a finite-element model. At first, the calculated representative stress-strain data pairs are analytically described to obtain true  $\sigma$ - $\varepsilon$  curves, Figure 8. The piecewise defined function according to Equation (8) is applied to fit the data pairs of the different hardness values. The yield strength of the related true stress-strain curve is then assessed by the intersection point between the linear-elastic domain (Hooke's law) and the flow curve (Hollomon's law) [6, 8, 14 29]. The curve of the elastic modulus is typically shifted by a strain offset value of  $\varepsilon_{\rm off} = 0.2\%$  to define the yield stress as the 0.2% proof strain  $R_{p0.2}$ . However, there is a clear disadvantage of Hollomon's law when describing the plastic regime. Due to its mathematical characteristics, the function tends to underpredict the yield stress, Figure 9a. As a result, it cannot correctly describe the true stress-strain curve in the transition area from elastic to plastic material behaviour [6, 15, 41]. In the literature, one correction method is proposed to approach this problem. The curve of the elastic modulus is shifted to higher offset values depending on the shape of the material's true  $\sigma$ - $\varepsilon$  curve, which is known from uniaxial tensile tests [6]. In this study, the offset value  $\varepsilon_{off}$  is determined by defining the stress at the intersection point for the reference hardness (H = 3.0 GPa) to be equal to the yield strength  $\sigma_{\rm v}$  of the electrical steel sheets. With the respective offset value and elastic moduli, the yield stress for the other hardness values can be subsequently obtained as well, Figure 9b. Besides the onset of yielding, the ultimate tensile strength can be assessed by the theory of instability in tension [8, 14, 23, 29]. In accordance, the representative strain at maximum load  $\varepsilon_{r,uts}$  is equal to the strain-hardening exponent n and the ultimate tensile strength  $\sigma_{\rm uts}$  (expressed in engineering stress) can be written as:

$$\sigma_{\rm uts} = \frac{K \cdot n^n}{{\rm e}^n} \tag{9}$$

Taking a closer look on the parameters for the analytical description of the true  $\sigma$ - $\varepsilon$  curves, it can be noted that with increasing hardness, not only the strength coefficient *K* but also the strain-hardening exponent *n* rises, Table 3. The different strain hardening slopes are accurately described by Hollomon's law [41]. As might be expected, there is a clear correlation between the calculated yield stress and ultimate tensile strength of the electrical steel sheet and the hardness.

After describing the  $\sigma$ - $\varepsilon$  curves, the investigated hardness profile of the punched electrical steel sheet has to



**FIGURE 9** Analytical description of the stress-strain data pairs by Hollomon's law, a) strain offset correction, b) flow curves for the different investigated hardness values.

**BILD 9** Analytische Darstellung der Spannungs-Dehnungs-Datenpaare nach Hollomon, a) Dehnungs-Offset Korrektur, b) Fließkurven für die unterschiedlichen betrachteten Härtewerte.

521

be converted into a mathematical model, which correlates hardness and local coordinates with reference to the punched edge. In this context, the hardness profile is interpreted as a function  $H = f(x^{(l)}, y^{(l)})$ , Figure 5. For the purpose of this study, a linear spline interpolation is performed in Python 3.9 using the radial basis function interpolator of the sub-package *scipy.interpolate*, Figure 10. As a result, the hardness in the punched electrical steel sheet can be interpolated for arbitrary local coordinates  $(x^{(l)}, y^{(l)})$ . Values outside the range of the measuring grid are conservatively extrapolated by means of a polynomial of variable degree, which is set to zero for the present application.

**TABLE 3** Parameters of the calculated true-stress strain curves with respect to the hardness.

**TABELLE 3**Parameter der berechneten wahren Spannungs-<br/>Dehnungs-Kurven in Bezug auf die Härte.

H [GPa]	K [MPa]	n [-]	$\sigma_{\rm y}~[{\rm MPa}]$	$\sigma_{\rm uts}$ [MPa]
3.0	842	0.16	440	538
3.5	1087	0.20	489	643
4.0	1207	0.18	586	740
4.5	1347	0.19	629	806
5.0	1390	0.17	705	862
5.5	1776	0.23	707	1010
6.0	1946	0.22	810	1115



**FIGURE 10** Mathematical model of the measured hardness profile determined by linear spline interpolation.

**BILD 10** Mathematisches Modell des gemessenen Härteprofils ermittelt durch lineare Spline-Interpolation.

### 4.2 | Modelling approach and simulation procedure

After the nanoindentation test data has been further processed, the modelling approach for the finite-element simulation of punched electrical steel sheets can be addressed. The modelling of the hardness profile requires an automated (scripted) procedure to enable an efficient implementation in commercial finite-element simulation programs. Regarding the simulation setup, an extended pre-processing is performed, which builds the basis for the material model assignment depending on the hardness, Figure 11. In order to accurately represent the hardness distribution in the area of the punched edge, the model has to provide a high mesh resolution and regular mesh structure. As a recommendation for the element size of hexahedrons, the resolution of the experimental measuring grid can be used. After the meshing is performed, the coordinates of the nodes are identified in the global *x-y-z* coordinate system.

Based on the information of the coordinates, the perpendicular distance of every node is calculated with respect to the punched edge, which corresponds to the local coordinate  $x^{(l)}$ , Figure 10. The local coordinate  $y^{(l)}$ describes the position with respect to the sheet thickness



FIGURE 11 Simulation flow chart for the modelling of the hardness profile.

BILD 11 Simulationsablaufdiagramm für die Modellierung des Härteprofils.

— WILEY. vch

522

and equals the nodes' global y-coordinates. With the coordinate pair  $(x^{(l)}, y^{(l)})$ , the node-by-node calculation of corresponding hardness values can be performed according to the function  $H = f(x^{(l)}, y^{(l)})$ . In a subsequent step, the elastic-plastic material properties are determined by using the correlation between the hardness and the true  $\sigma$ - $\varepsilon$  curves. In this study, the elastic moduli and true  $\sigma$ - $\varepsilon$  curves are provided between H = 3.0 GPa and 6.0 GPa in 0.5 GPa steps, Figure 9b. When a node's associated hardness value lies between the given values, the elastic modulus *E* and parameters describing the true  $\sigma$ - $\varepsilon$  curve, are interpolated. For values which lie outside the defined reference or maximum hardness, the material parameters are not extrapolated. Instead, the reference and maximum hardness are assumed as limit values.

The material model is entered in tabular form assigning the location-dependent elastic-plastic material properties to the respective nodes. Linear-elastic behaviour is defined by the elastic modulus *E* and the Poisson's ratio  $\nu$ . The plasticity formulation includes the flow curve  $\sigma$ - $\varepsilon_{\rm pl}$  starting from the yield stress  $\sigma_{\rm y}$  at zero plastic strain. Plastic strain values  $\varepsilon_{\rm pl}$  are obtained by subtracting the elastic  $\varepsilon_{\rm el} = \sigma_{\rm r}/E + \varepsilon_{\rm off}$  from the total strain  $\varepsilon_{\rm r}$ . For the purpose of this study, the flow curves are defined until a plastic strain of 15%.

After the pre-processing, the model can be solved. Due to the local fine mesh resolution and the locationdependent material model assignment, the related simulation files can become large. It should therefore be considered that enough computing capacity is provided for the pre- and postprocessor as well as for the solver. In the context of postprocessing, the implemented hardness distribution should be plotted for a comparison with the experimental data. Thus, a sufficient local resolution of the material model assignment can be ensured. Finally, the loading condition and elastic-plastic material behaviour is evaluated in terms of the local stress distribution at the punched edge.

#### 5 | FINITE-ELEMENT MODEL IMPLEMENTATION IN ABAQUS

#### 5.1 | Simulation setup

The presented modelling approach for the simulation of the hardness profile of punched electrical steel sheets is performed using the Abaqus/CAE software environment. Within the scope of this study, the considered electrical steel sheet specimen is represented as quarter model and analysed in a three-dimensional static simulation, Figure 12. The high mesh resolution and desired



**FIGURE 12** Simulation model of the electrical steel sheet specimen, a) meshing of quarter specimen, b) representation of local coordinate system and punched edge, the latter highlighted by a yellow line.

**BILD 12** Simulationsmodell der Elektroblechprobe, a) Vernetzung der Viertelprobe, b) Darstellung des lokalen Koordinatensystems und der Stanzkante, letztere durch eine gelbe Linie hervorgehoben.

regular structure is achieved by partitioning the specimen along the punched edge in a distance of 0.5 mm from the cutting line. The partition is then meshed using general-purpose hexahedron elements of type C3D20R (20 nodes, reduced integration) with constant element edge lengths of  $20 \,\mu\text{m} \cdot 20 \,\mu\text{m} \cdot 50 \,\mu\text{m}$ , Figure 12a. The remaining part of the specimen exhibits a considerably smaller mesh resolution including element sizes of  $500 \,\mu\text{m} \cdot 270 \,\mu\text{m} \cdot 1000 \,\mu\text{m}$ . Both meshes are merged by means of a tie constraint, which enables the rapid transition of the different element dimensions. The boundary conditions correspond to the setup of a uniaxial tensile test applying the monotonic loading at the upper end of the specimen under stress-control.

The coordinates of the nodes and their perpendicular distance to the punched edge are identified by using Abaqus Python commands. For this purpose, the punched edge is defined as node set and the method *getClosest()* is applied to determine the perpendicular distance  $x^{(l)}$ , Figure 12b. As mentioned before, the nodal position with respect to the sheet thickness  $y^{(l)}$  equals the global y-coordinate and can be accessed through the Abaqus Python command *nodes[].coordinates*. A list including the node IDs and local coordinates  $(x^{(l)}, y^{(l)})$  is exported for the external calculation of the related hardness values  $H = f(x^{(l)}, y^{(l)})$  with Python 3.9 using the sub-package *interpolate* of the *scipy* library. After that, information about the nodes' hardness values is provided for the subsequent interpolation of corresponding

material properties, which is again performed in the Abaqus/CAE software environment (Abaqus Python command *numpy.interp*).

The location-dependent material properties are combined in one material model definition by assigning a field variable to the inserted tabular data. In order to reduce the computational cost, material properties are not specified for every calculated hardness value. Instead, they are provided for hardness values in steps of 0.01 GPa between the reference and maximum hardness. The correct assignment of the material properties to the respective nodes is then accomplished by the definition of a discrete field, which links field variable and node ID (Abaqus Python method DiscreteField ()). The modelling approach described in this study does not consider the geometric characteristics of the punched edge. The punched edge is modelled in an idealised way assuming a perfect rectangular cross-section of the electrical steel sheet. However, the location-dependent material model assignment can also be performed under consideration of the actual punching edge geometry, including rollover, shear and fracture zone.

### 5.2 | Results and validation with experimental data

The resulting hardness profile is verified by comparing the implemented hardness values at the nodes with the experimental input data, Figure 13. The modelling approach is in good alignment with the actual hardness distribution in the area of the punched edge. Due to the quadratic shape function of the applied elements, the distance between the nodes in the  $x^{(l)}-y^{(l)}$ -plane is 10 µm, which meets the resolution of the experimental measuring grid, Figure 13a. Minor differences result from the mathematical processing of the experimental input data and the related interpolation of hardness values, Figure 13b. The corresponding elastic-plastic material properties, which have been assigned to the nodes, are automatically interpolated at the material integration points by Abaqus [43]. As a result, the material behaviour of a C3D20R element equals the superposition of the defined material behaviour at its  $2 \cdot 2 \cdot 2$  integration points.

After the verification of the modelled hardness profile, the stress-strain response in the area of the punched edge is analysed. In a first step, only the linear-elastic material behaviour is considered by applying a nominal stress of 340 MPa, Figure 14a. The von Mises equivalent stress distribution of the electrical steel sheet specimen is plotted in the  $x^{(l)}-y^{(l)}$ -plane at the point of the global maximum stress. The highest stress occurs close to the punched edge with a stress increase of about 30%. Moreover, the comparison of the stress distribution with the implemented hardness profile shows a clear correlation between the magnitude of hardness and stress, Figure 13. However, when considering the evolution of the equivalent stress  $\sigma_{\rm eqv}$  and principal strain  $\varepsilon_1$  along the  $x^{(l)}$ -direction, even though the stresses are affected, the strain remains constant. Regarding the elastic-plastic material behaviour, a nominal stress of 500 MPa is applied and the stress-strain response of the electrical steel sheet specimen is evaluated as before, Figure 14b. Despite the higher stresses and presence of plastic strain, the von Mises equivalent stress distribution as well as the evolution of  $\sigma_{eqv}$  and  $\varepsilon_1$  along the  $x^{(l)}$ -direction show a similar characteristic.



FIGURE 13 Comparison of hardness profile, a) modelled distribution including location of nodes, b) experimental input data.
BILD 13 Vergleich des Härteprofils, a) modellierte Verteilung einschließlich Darstellung der Knoten, b) experimentelle Eingangsdaten.



FIGURE 14 Stress-strain response of the punched electrical steel sheet specimen, a) linear-elastic behaviour, b) elastic-plastic behaviour.

**BILD 14** Spannungs-Dehnungs-Antwort der gestanzten Elektroblechprobe, a) linear-elastisches Verhalten, b) elastisch-plastisches Verhalten.

The observed stress-strain response can be explained by the fact that the deformation behaviour is primarily determined by the unaffected base material, which comprises the much larger portion of the material volume. Thus, the area of the punched edge exhibits the same magnitude of strain as the base material. A constant strain, however, results in a different stress response of the nodes depending on the assigned material properties. The higher the elastic modulus in case of a linear-elastic behaviour, the higher the stress response. The same applies for the elastic-plastic regime regarding the true  $\sigma$ - $\varepsilon$ curves and magnitude of the flow stresses. Since the nodes with the highest hardness values and consequently the highest elastic moduli and flow stresses lie close to the punched edge, the stress response is increased. Besides, the local assignment of different material properties results in an additional notch effect. Due to that, stress concentrations occur, especially at locations with distinct gradients of adjacent material properties.

The validation of the simulated hardness profile with experimental data proves to be difficult, since the local recording (e.g., digital image correlation) of stress and strain in the  $x^{(l)}-y^{(l)}$ -plane of the electrical steel sheet is not practicable. One alternative regarding the indirect

evaluation of the influence due to the punched edge is the consideration of uniaxial true stress-strain curves. For this purpose, the representative true stress-strain curve of a punched electrical steel sheet specimen is compared with a smooth specimen, which is processed by high precision electrical discharge machining, Figure 15. Simulation results for the smooth specimen are obtained by applying the presented modelling approach with a uniform material model assignment related to the reference hardness. The experimental data shows a small increase of about 5 MPa regarding the global stress response of the punched specimen. The simulation (stress-controlled loading with nominal stress of 625 MPa, no modelling of failure) predicts a similar shift of the stress-strain curve to higher stress values, whereas the difference between punched and smooth specimen of 11 MPa to 20 MPa is over-predicted to some extent. This can be explained by the fact that the simulation in this study does not consider the complex geometry and surface condition of the punched edge. Moreover, minor differences can be expected due to the analytical description of the material model input data with the piecewise defined function including the prestrain offset method. sented Nevertheless, the



**FIGURE 15** True stress-strain curve of reference and punched electrical steel sheet specimen according to simulation results and experimental data.

**BILD 15** Simulierte und experimentelle wahre Spannungs-Dehnungs-Kurve der Referenz- und der gestanzten Elektroblechprobe.

comparison with experimental data basically confirms the simulation results and predicted influence of shear cutting on the monotonic material behaviour.

#### 6 | CONCLUSION

In this study, a modelling approach for the simulation of the hardness profile of punched electrical steel sheets has been presented. Strain hardening and plastic deformation due to the shear cutting process affect the mechanical material behaviour, which is considered by locally adjusting the elastic-plastic material properties depending on the hardness distribution. Spherical nanoindentation tests have been performed to determine load-displacement curves in the area of the punched edge. Besides the hardness and elastic moduli, representative stress-strain data is obtained by applying Tabor's concept of indentation stress-strain curves. In this context, the corresponding stress- and strain-constraint factors are verified by calibration with experimental tensile test data.

The magnitude of the original stress constraint factor according to Tabor's approach is too small, which can be explained by the well-known indentation size effect. Due to that, an adjusted value is determined for the subsequent calculation of representative stress. Regarding the representative strain, sink-in and pile-up phenomena are taken into account for defining the contact radius. Strain values are calculated using a strain-constraint 525

ĥt

) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons

factor of  $\beta = 0.2$ , which prove to be consistent with the definition of Ahn and Kwon. The obtained stress-strain data pairs are analytically described by a piecewise defined function, including Hooke's law in the elastic regime and Hollomon's strain-hardening function in the plastic regime. For the better description of the onset of yielding, a strain offset value has been introduced.

On this basis, corresponding elastic-plastic material properties are assigned according to the presented simulation procedure. Numerical simulations of a punched electrical steel sheet specimen under monotonic loading have been performed in Abaqus, which allow for an accurate representation of the hardness profile in the area of the punched edge. It can be observed that the material behaviour shows an increase in the stress response with increasing hardness. Finally, the validation by means of experimental true stress-strain curves indicates the correct representation of the relations between hardness and elastic-plastic material properties. In further works, an extension of the modelling approach for the simulation of cyclic loading would be conceivable using a suitable hardening model as presented elsewhere [44].

#### ACKNOWLEDGMENTS

This study was performed as part of the research project "Schwingfestes Elektroblech" funded by the Federal Ministry of Education and Research (BMBF) and the Audi AG. The present work was developed at the Technische Hochschule Ingolstadt in cooperation with the Otto-von-Guericke-Universität, Magdeburg. Open Access funding enabled and organized by Projekt DEAL.

#### ORCID

P. Kubaschinski 🕩 http://orcid.org/0000-0001-5433-8267

#### REFERENCES

- H. Dehmani, C. Brugger, T. Palin-Luc, C. Mareau, S. Koechlin, Procedia Eng. 2015, 133, 556.
- S. V. A. Laakso, A. Väänänen, S. Bossuyt, A. Arkkio, presented at *FAIM2016*, Seoul, Republic of Korea, June 27 – June 30, 2016.
- 3. N. E. Dowling, S. L. Kampe, M. V. Kral, *Mechanical Behavior* of *Materials*, Pearson, Harlow **2019**.
- D. Tabor, *The Hardness of Metals*, Oxford University Press, Oxford 2000.
- 5. S. Pathak, S. R. Kalidindi, Mater. Sci. Eng. R 2015, 91, 1.
- M. Beghini, L. Bertini, V. Fontanari, Int. J. of Solids Struct. 2006, 43, 2441.
- 7. P. Zhang, S. X. Li, Z. F. Zhang, Mater. Sci. Eng. A 2011, 529, 62.
- 8. M. O. Lai, K. B. Lim, J. Mater. Sci. 1991, 26, 2031.
- A. C. Fischer-Cripps, Introduction to Contact Mechanics, Springer, New York 2000.
- M. F. Ashby, D. R. H. Jones, *Engineering Materials 1*, Butterworth-Heinemann, Oxford **2012**.

15214052, 2023, 4, Down from https: .wiley 1002/maw 202200283 by Technische Hochschule Ingolstadt, Wiley Online Library on [09/08/2023]. See the Terms Wiley Online Library for rule use; OA are governed by the applicable Creative

- WILEY₌vch
- 11. H. E. Boyer, T. L. Gall (Eds.), *Metals Handbook*, ASM, Metals Park **1985**.
- 12. W. D. Callister, D. G. Rethwisch, *Materials Science and En*gineering, Wiley, Hoboken **2011**.
- C. Chang, M. A. Garrido, J. Ruiz-Hervias, Z. Zhang, L. Zhang, Adv. Mater. Sci. Eng. 2018, 2018, 8316384.
- A. Ruiz-Moreno, P. Hähner, F. Fumagalli, V. Haiblikova, M. Conte, N. Randall, *Mater. Des.* 2020, 194, 108950.
- C. Moussa, X. Hernot, O. Bartier, G. Delattre, G. Mauvoisin, J. Mater. Sci. 2014, 49, 592.
- M. Beghini, L. Bertini, V. Fontanari, B. D. Monelli, *Procedia* Eng. 2011, 10, 1679.
- 17. E. Meyer, Z. Ver. Deutsche Ing. 1908, 52, 645.
- J. L. Loubet, J. M. Georges, G. Meille, in *Microindentation Techniques in Material Science and Engineering*, (Eds. J. B. Blau, B. R. Lawn), ASTM STP 889, Philadelphia **1986**, 72–89.
- Y. Tirupataiah, G. Sundararajan, *Metall. Trans. A* 1991, 22 A, 2375.
- 20. A. C. Fischer-Cripps, J. Mater. Sci. 1997, 32, 727.
- 21. B. Taljat, T. Zacharia, F. Kosel, Int. J. Solids Struct. 1998, 35, 4411.
- 22. A. E. Giannakopoulos, S. Suresh, Scr. Mater. 1999, 40, 1191.
- 23. J. Ahn, D. Kwon, J. Mater. Res. 2001, 16, 3170.
- 24. H. Hertz, J. angew. Math. 1882, 92, 156.
- 25. W. C. Oliver, G. M. Pharr, J. Mater. Res. 1992, 7, 1564.
- 26. I. N. Sneddon, Int. J. Eng. Sci. 1965, 3, 47.
- 27. M. Sun, C. Tan, W. Tan, C. Yang, J. Phys. Conf. Ser. 2020, 1637, 012042.
- I. Matsuya, R. G. G. Fatt, I. Ihara, J. Solid Mech. Mater. Eng. 2013, 7, 155.
- J. Kim, K. Lee, J. Lee, D. Kwon, Surf. Coat. Technol. 2006, 201, 4278.
- R. Hill, B. Storakers, A. B. Zdunek, P. Roy. Soc. Lond. 1989, 423, 301.
- 31. J. H. Hollomon, Trans. Met. Soc. AIME 1945, 162, 268.

- 32. S. Jayaraman, G. T. Hahn, W. C. Oliver, C. A. Rubin, P. C. Bastias, *Int. J. Solids Struct.* **1998**, *35*, 365.
- P. Ludwik, *Elemente der technologischen Mechanik*, Springer, Berlin 1909.
- W. Ramberg, W. R. Osgood, Natl. Advis. Comm. Aeronaut., Tech. Notes 1943, Technical Note No. 902.
- A. Gottwalt, P. Kubaschinski, M. Waltz, U. Glatzel, U. Tetzlaff, *Int. J. Fatigue* 2022, *162*, 106987.
- T. Chudoba, in *Nanostructured Coatings*, (Eds.: D. J. Lockwood, A. Cavaleiro, J. T. M. De Hosson), Springer, New York 2006, 216–260.
- B. Ernst, S. Keim, U. Tetzlaff, Mater. Sci. Eng. A 2022, 848, 143392.
- H. Jiang, Z. Ren, Y. Yi, L. He, S. Yuan, J. Mater. Res. Technol. 2021, 14, 1065.
- 39. H. Lan, T. A. Venkatesh, Philos. Mag. 2014, 94, 35.
- L. Veleva, P. Hähner, A. Dubinko, T. Khvan, D. Terentyev, A. Ruiz-Moreno, *Nanomater*. 2021, 11, 71.
- 41. E. G. Herbert, W. C. Oliver, G. M. Pharr, *Philos. Mag.* 2006, *86*, 5521.
- 42. G. Z. Voyiadjis, M. Yaghoobi, Crystals 2017, 7, 321.
- Dassault Systèmes Simulia Corp., Abaqus Documentation 2020: Defining general material data 2020, Dassault Systèmes, France.
- 44. P. Kubaschinski, A. Gottwalt, U. Tetzlaff, H. Altenbach, M. Waltz, *Materialwiss. Werkstofftech.* **2022**, *53*, 422.

How to cite this article: P. Kubaschinski, A. Gottwalt-Baruth, U. Tetzlaff, H. Altenbach, M. Waltz, *Materialwiss. Werkstofftech.* **2023**, *54*, e202200283. https://doi.org/10.1002/mawe.202200283