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An experimental setup for fatigue testing of thin electrical steel sheets

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ABSTRACT

In this study, the fatigue behavior of thin electrical steel sheets under cyclic loading is investigated. Results from strain-controlled and stress-controlled fatigue tests with different specimen geometries and different test setups are presented and compared with conventional testing methods. The results imply that conventional testing methods should be adjusted for testing thin electrical steel sheets because the fatigue life depends significantly on the test setup as well as the specimen geometry. Therefore, this study proposes an improved specimen geometry and test setup for stress- and strain-controlled fatigue tests of thin electrical steel sheets depending on the desired testing parameters.

1. Introduction

The increasing awareness of sustainable mobility combined with technical limitations in the development of internal combustion engines are causing the switch to alternative drive concepts, such as the electrification of the drivetrain. The cores of electric motors consist of stacked thin electrical steel sheets. The soft magnetic properties and the increased electrical resistance of this material compared to pure iron are essential for performance and efficiency. Contrary to the requirements for stationary industrial electric motors, extended design criteria apply to electric motors in the automotive industry due to higher rotational speeds. Mechanical stresses primarily emerge from centrifugal forces from high rotational speeds during operation. Consequently, the design of electrical steels for the automotive industry is not purely focused on magnetic properties. Instead, the combination of proper electromagnetic and mechanical properties is necessary.

Because of the small thickness, usually in the range of 0.2 to 0.4 mm, electrical sheet specimens are fragile. Therefore, stability, i.e. resistance to buckling, becomes relevant for fatigue testing with compression forces. In general, the cyclic loading in fatigue tests can either be symmetric or asymmetric and strain- or stress-controlled. Symmetric strain-controlled cycling in the plastic domain, commonly referred to as low-cycle fatigue, results in high compressive forces. Testing of thin specimens under compression is difficult because of their tendency to buckle. The main factors influencing buckling are the amount of stress, buckling length, modulus of elasticity, specimen thickness and the clamping conditions. Most of these factors are prescribed, and even the buckling

length cannot be reduced arbitrarily, as space is needed for the attachment of extensometers. To minimize the risk of buckling under compression loads, authors often use miniaturized specimens with reduced length-to-width ratios and small radii [1,2]. Corresponding effects due to reduced specimen size are frequently investigated and can be relatively small for a homogeneous material with fine surface finishing and for certain loading types [2–7]. The surface finishing conditions are particularly important for fatigue testing of such miniaturized specimens because surface quality is expected to have a more pronounced effect on the fatigue life of small specimens than on bulk specimens [3]. As electrical sheets are usually punched, the mechanical deformation at the punched edge is even more pronounced by using miniature specimens [8,9]. Therefore, to reduce the influence of the specimen size effect, a small specimen width is not recommended if punched specimens are being tested. Furthermore, the average grain size of electrical sheets is comparably large (50 µm to 200 µm), which increases the scatter for micro specimens due to lower grain statistics [10]. Therefore, reducing the specimen width to avoid buckling is not an available option for punched electrical steel sheets.

Another approach to reduce buckling of electrical steel sheets is by packaging of multiple individual samples. However, this approach tends to underestimate the number of cycles to failure due to the weakest link concept [11].

In summary, both approaches fail to provide good results in the case of punched electrical steel sheets, which is why usage of an anti-buckling restraint is indispensable. The use of anti-buckling restraints for flat specimens is mentioned in international standards. The standard E606

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from the American Society of Testing and Materials (ASTM) recommends the use of an anti-buckling support, whereby its design should be adapted to the specific specimen geometry and extensometer [12]. The International Organization for Standardization (ISO) describes in ISO 12,106 the geometric design of the buckling support in more detail and recommends a friction-reducing coating in the form of polytetrafluoroethylene (PTFE) foil with a thickness of 1.0 mm [13].

Apart from the test setup itself, the standardized specimen geometries also have certain limitations. There are several reasons for this, the main one being the stress distribution of the standard fatigue test specimens. Constructively caused notches with the resulting stress concentration act as superimposed, undesired effects. ASTM E606 defines the geometry of a flat specimen based on its thickness T, whereas the radius of the gage to grip transition R is defined as $R = 2 T \pm T/2$ [12]. As a result of the small radius for very thin specimens, a high stress concentration at the gage-to-grip transition builds up. To reduce the possibility of crack initiation in the gage-to-grip transition region, an increase of the radius decreases the stress concentration. The national standard Stahl-Eisenprüfblatt (SEP) 1240 [14] achieves a significantly lower stress concentration factor with its radius specification of 25 mm. The maximum stress lies thereby always in the gage-to-grip transition and thus not in the parallel measuring range where the extensometer is mounted. This stress gradient problem of most standardized specimens (not only for the application of electrical sheets) is well-known [15]. Specific specimen geometries bypass the issue of notch effects by avoiding a parallel gauge region as a continuous radius can shift the maximum stress to the exact center of the specimen. European Standard EN 6072 provides such a recommendation of a specimens with no parallel measuring range and a transition radius of 100 mm [16]. However, this results in disadvantages, since that there is no longer a specific material volume in which the material behavior can be analyzed without the influence of geometrical effects. Especially for strain-controlled fatigue tests, such a specimen geometry is not ideal because the local strain and thus the local stress in the center of the specimen is always higher than the strain amplitude measured by an extensometer. This problem results from the increasing cross section area with increasing distance from the center.

As far as the mechanical testing of electrical sheets is concerned, no uniform procedure has been established for determining fatigue properties of thin electrical steel sheets, partly for the reasons mentioned above. Instead, most authors prefer to use their own specimen geometry and test setups [17–21]. To contribute in the direction of a uniform test procedure, an improved fatigue testing method and an optimized specimen geometry for both, strain- and stress-controlled fatigue tests, are proposed.

2. Material

The material used in the present investigation is a fully processed non-oriented electrical steel sheet with a nominal thickness of 270 μ m. The manufacturing process includes the following steps: hot rolling, cold rolling and annealing. The chemical composition and monotonic material properties are given in Table 1 and Table 2, respectively.

Fatigue tests are performed with smooth specimens, which are processed from the delivered sheet material by high precision electrical discharge machining (EDM) or high precision laser cutting. Machining of the rolled surface is not performed, as a significant amount of crosssection would be lost, as well as the specific properties of the rolling process, which can vary depending on the degree of deformation and the final annealing conditions. Furthermore, the coating process for

Table 1	l
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Elements	С	Mn	Si	Р	S	Al	Fe
wt.%	< 0.0045	0.16	3.32	0.01	0.002	1.1	95.3

Table 2

Monotonic material properties of the studied non-oriented electrical steel sheet in rolling direction.

E [GPa]	ν[-]	R _e [MPa]	R _m [MPa]	A [%]
187	0.28	447	540	15.3

applying the insulating coating on the surface can introduce residual stresses [22]. Therefore, the isolation coating should remain present in case of application-related fatigue testing of electrical steel sheets. Moreover, the rolled surface already has a low roughness with $R_z\approx 1.0\,\mu m$ and almost always cracks start at the specimen edge due to the geometrically related stress distribution. Consequently, it is not considered beneficial to change the condition of the rolling surface and thus the existing insulating coating is not removed for all fatigue tests performed in this study.

Low cycle fatigue (LCF) and high cycle fatigue (HCF) tests are performed utilizing an electric dynamic test machine ElectroPuls E10000 (INSTRON, High Wycombe, United Kingdom) with an extensometer EXA 10–0.5 (SANDNER-Messtechnik GmbH, Biebesheim am Rhein, Germany). The strain-gaged alignment fixture AlignPRO from INSTRON is used for verification of axial alignment according to ASTM E1012. Fastening of the screws in a controlled manner is achieved by using the fine torque wrench TorqueVarioS (Wiha Werkzeuge GmbH, Schonach, Germany). Tribological experiments were performed using a SRV4 test machine (Optimol Instruments GmbH, Munich, Germany). Numerical simulations were carried out with Dassault Systèmes Abaqus Software (Dassault Systèmes, Vélizy-Villacoublay, France).

3. Specimen geometry

For the manufacturing of standardized specimens, a fixed radius is often selected for the gage-to-grip transition, as it is easy to define and easy to be fabricated by basic machine tools like milling cutters. However, such machining processes are rarely used for electrical steel sheets due to their low thickness. Typical manufacturing processes for fatigue specimens of electrical steel sheets are waterjet cutting, laser cutting, eroding, and punching. Consequently, the design of the gage-to-grip transition can be done more freely and a smoother gage-to-grip transition by a specific contour instead of one fixed radius is possible to minimize the stress concentration. In addition to a low stress concentration, there are further requirements for the design of specimen geometries. For example: i) consideration of the gripping conditions to avoid pull out of the clamping jaws, ii) space availability on the respective testing machine, iii) mounting of extensometers and their gauge length, iv) localization of the damaging activity within the gauge length, v) low tendency to buckle by reducing the distance between the clamping jaws if compressive forces are applied.

It becomes apparent that there is a conflict of objectives between some requirements, which means that there is not a single perfect geometry but rather a different weighting of the requirements depending on the specific application. The aim in this study is to find an adequate solution for thin electrical steel sheets. Table 3 shows an overview of the investigated specimen geometries. For reasons of comparability, the total length and the width of gauge section are kept constant for all variants. The gauge lengths and the design of the gage-to-grip transition, on the other hand, are varied.

The stress concentration factor K_t of the considered specimen geometries is determined by finite-element analysis with the simulation software Abaqus. It is defined as the ratio of maximum stress σ_{max} and nominal stress σ_{nom} of the cross-section and can be interpreted as a measure of stress concentration due to the change in the flow of stress. Basically, the stress concentration factor is calculated under the consideration of linear-elastic material behavior, which is described by the Young's Modulus E and the Poisson's ratio ν_s see Table 2. In Fig. 1 a), the basic setup of the two-dimensional static simulation is shown for the

Table 3

Overview of the investigated specimen geometries with schematic drawing and stress concentration factor K_t.





Fig. 1. a) Two-dimensional FE-model of the electrical steel sheet specimen (quarter section of type V), b) Stress distribution at the specimen edge (path A-B) depending on the respective gage-to-grip transition, c) Stress distribution in the center of the specimen (path A-C).

specimen geometry according to type V. General-purpose shell elements of type S4R (four-node shell, reduced integration) with an element size of 1 mm are used for meshing. In the gage-to-grip transition, a reduced element size of 0.7 mm is applied according to mesh sensitivity studies. The boundary conditions correspond to the setup of a tensile test. The lower end of the specimen is fixed, while the uniaxial load is applied at the upper end of the specimen.

Type I is used as a standardized reference sample from the national standard SEP 1240 [14]. Type II has a larger radius than the reference sample by reducing the head length. Thus, stress concentration at the gage-to-grip transition is lower. Type III has the same geometry as type II, but without a parallel measuring range. This hourglass shape reduces

buckling during the compressive part of the cycle. However, only a small volume of the material is subjected to the maximal stress. Type IV has an even larger radius than type I and type II, facilitated by the additionally reduced head width. Type V is designed with three combined radii to achieve a homogeneous stress state with a minimized stress concentration factor. This gage-to-grip transition is based on Neuber's optimized profile of a double-sided symmetric lateral notch with constant edge stress [23]. It is described by an elliptic function with increasing curvature, which can be approximated by a combination of different radii [23,24]. Due to that, constructively caused stress concentrations can be significantly reduced, while the stress distribution in the measuring range is homogeneous. However, no parallel measuring range L₀ is considered in the design, which constitutes a disadvantage for the analysis of the material behavior, as mentioned before. In a preceding design phase, a sequence of three compatible radii has been combined with a reduced parallel measuring range resulting in a novel design approach for flat specimens. The measuring range consists of the parallel range L₀ and the quasi-parallel range represented by the large inner radius R300. See Table 3 for the exact dimensions of the developed gageto-grip transition. With a gauge length of 4 mm, it can be ensured that the maximum stress, which occurs at the transition from L_0 to R300, lies between the extensometer's knife edges. Due to the large inner radius, the expansion of the nominal cross-section in the measuring range is negligible. Type VI and VII are similar, besides the initial gage length. For both types, the gage-to-grip transition is designed by a smooth spline. Type VIII is characterized by a very short transition range to increase resistance to buckling. This is implemented by an exponential function.

For a detailed comparison of the different specimen geometries, the simulated stress distribution under linear-elastic material behavior is analyzed. The von Mises equivalent stress standardized to the nominal stress at the specimen edge (path A-B) is shown in Fig. 1 b).

Besides the magnitude of the respective stress concentration factors, the location of the maximum stresses can be identified by the stress curves. It becomes evident that type V shows not only the smallest stress concentration factor, but also a nearly constant stress distribution in the first third of the specimen edge ($0 < s/L_1$ ratio < 0.33). The maximum stress is located between the parallel measuring range L₀ and the onset of the gage-to-grip transition. Due to that, a longer parallel measuring range results in a shift of the maximum stress from near the center of the specimen to bigger s/L ratios. This proves to be disadvantageous, since the gauge length of the extensometer is limited, and the maximum stress may not be captured. Type III and VIII have no parallel measuring range. The stress curve corresponding to the specimen with exponential gageto-grip transition shows the highest stress concentration factor. With the hourglass shaped specimen geometry, type III displays a special case, since the maximum stress lies exactly in the center of the specimen (s/L = 0).

Moreover, the von Mises equivalent stress curves in the center of the specimens (path A-C) illustrate the stress gradients caused by the gage-to-grip transitions, see Fig. 1 c). As a result of the stress concentration, the stress distribution in the nominal cross-section is affected. Especially type III shows a steep stress gradient with higher stresses at the specimen edge ($s/L_2 = 0$) and reduced stresses in the center ($s/L_2 = 1$). For the specimen geometries with a parallel measuring range, the influence of the stress gradient is only minor. However, it can be noted that a gage-to-grip transition defined by increased radii or a smooth spline reduces the stress gradient compared to the reference sample (Type I).

After the simulation of the stress distribution under linear-elastic material behavior, a non-linear buckling analysis is performed to evaluate the buckling resistance of the specimen geometries under compressive load. The two-dimensional static simulation setup, see Fig. 1 a), builds the basis and is extended by material and geometric nonlinearity. The degrees of freedom (DOF) in the specimen's clamping area are constrained and a displacement controlled compressive load is applied in negative z-direction at the upper end of the specimen. To

ensure a converging solution, automatic time incrementation is used and the maximum time increment is set to $1 \cdot 10^{-3}$ of the step time. Moreover, geometric imperfections are considered by superimposing the respective specimen geometries with their first buckling eigenmode, which is determined in a previous linear buckling analysis. The magnitude of the geometric imperfection is specified as $1 \cdot 10^{-3}$ mm (1/270 of the sheet thickness). The results of the buckling analysis are shown in Fig. 2 a) in the form of force–displacement curves.

Considering the buckling mode, it is characterized by the loss of structural integrity in the center of the specimen geometry, see Fig. 2 b). In the force–displacement plot, this failure can be identified as the domain where the reaction force cannot be further increased. For thin steel sheets without the use of an anti-buckling restraint, this structural failure already occurs under small compressive loads. It becomes clear that the buckling resistance directly depends on the length of the gage-to-grip transition. With the smallest gage-to-grip transition, type VIII allows for a buckling load which is significantly higher than the buckling load of the other specimen geometries.

After the maximum reaction force is reached, a decline of the force–displacement curve can be observed. However, the other specimen geometries with smaller buckling loads do not show such a strong decline. According to the results of the buckling analysis, it can be noted that a shorter gage-to-grip transition tends to increase the buckling resistance of the specimen under compressive loads.

Of the investigated variants, a pre-selection of variants on which fatigue tests are carried out is made based on the results shown concerning the stress concentration factor and buckling behavior. Type II is not considered further because the stress concentration factor is higher compared to other variants, and thus, only a slight improvement is expected compared to the reference condition. Type IV is also not examined closely because a more increased tightening torque is necessary to firmly clamp the specimens due to the reduced specimen head width. However, higher tightening torques increase the tendency for a superimposed torsional load through the clamping system. Furthermore, the fatigue life of type VII is not investigated due to its similarity to type VI. Stress-controlled fatigue tests are performed with a frequency of 40 Hz, load ratio of R = 0.1 and nominal stress amplitude of $\sigma_a = 225$ MPa without considering the stress concentration factor, i. e. all geometries are loaded with the same force. It is noticeable that relatively high numbers of cycles are achieved despite the upper stress value ($\sigma_{max} =$ 500 MPa for $\sigma_a=225$ MPa and $R_{\sigma}=0{,}1)$ being approximately 50 MPa higher than the yield strength of 447 MPa. This behavior is commonly seen for fatigue loaded electrical steel specimens [17,25] and is related to the pronounced strain rate sensitivity and positive stress ratios. Fig. 3 shows the fatigue life as a function of the specimen geometry for the selected types.



Fig. 2. a) Nonlinear buckling analysis of the different specimen geometries under consideration of a geometrical imperfection, b) visualization of the corresponding buckling mode for type I.



Fig. 3. Numbers of cycles to failure with standard deviation for different specimen geometries without anti-buckling restraint.

The mean cycles to failure N_f for the specimen type I are 210692 cycles which is set as a reference. Other specimens are considered in relation to this reference. Higher stress concentration factors can have a detrimental effect on the fatigue life, as shown by type VIII. Here, the stress concentration would significantly underestimate the material fatigue strength, as only 12.4% of the reference fatigue life is achieved. Type VI has a slightly higher fatigue life compared to the reference. Regarding the estimated standard deviation however, the difference is not significant. Type III and especially type V show a significantly increased fatigue life of 21% and 61%, respectively. However, in addition to the highest cycle count, type V also had the highest scatter of measured values.

4. Modified test setup

As input parameters for service life estimation with the local strain approach, strain-controlled fatigue tests with a load ratio of -1 are

commonly used [26]. Therefore, testing with high compressive forces is necessary. Depending on the sheet thickness and the material, flat specimens tend to buckle in the compression part of the hysteresis cycle. Due to the low thickness of the electrical steel sheets, an anti-buckling restraint is necessary even at low compression forces to avoid buckling. The anti-buckling restraint stabilizes the specimen and can prevent buckling to a certain extent. However, the characteristics of the test setup and the anti-buckling restraint can significantly influence the measured data. In this study, the standardized approach for fatigue testing of flat specimens according to SEP 1240 is picked up and extended for the application of electrical steel sheets. The resulting experimental setup with adjustments can be seen in Fig. 4. The two halves of the anti-buckling restraint are fastened by up to six M4 screws onto the sample. In the context of preliminary tests, it turned out to be beneficial if the system of the anti-buckling restraint is mounted in a floating manner, i.e., the fastening takes place directly on the oscillating specimen. However, this can cause the position of the anti-buckling support to change slightly in the course of the cyclic test, resulting in the risk of losing contact between the knife edges of the extensometer and the specimen. To avoid this, either a higher tightening torque can be selected, or the movement of the anti-buckling restraint should be limited in vertical and horizontal direction. As high tightening torques can be disadvantageous (see chapter 4.1.) unintended movement is avoided in the horizontal direction by two guide rails. A PTFE-foil is used at the sliding contact between the vertical guide rails and the antibuckling restraint to reduce friction. A small gap must remain between the anti-buckling restraint and the clamping jaws to avoid local buckling but also to allow unrestricted extension and compression of the specimen at maximum load. Therefore, the gap should be adjusted to approximately 0.5 to 1.0 mm. Furthermore, soft polymer plates are inserted in both gaps to restrict unintended movement of the antibuckling restraint in the vertical direction.

In general, for fatigue testing of sheet specimens, an extensioneter should preferably be mounted on one face of the specimen rather than on the edge since there is the instability of the attachment due to the thin edge of 0.30 mm or even less. However, due to the anti-buckling restraint, the positioning of the extensioneter is only possible on the small edges of the samples. Nevertheless, by using tension springs for proper



Fig. 4. Experimental setup for fatigue testing, a) machine setup, b) detailed view of the anti-buckling restraint and specimen (yellow contour), c) exploded view with partly removed components.

mounting, no slippage of the extensometer occurs. However, it should be noted that the small contact area between the cutting edge of the extensometer and the specimen edge can lead to high local surface pressures in the contact area. The probability of a fatigue crack occurring below the cutting edges increases with higher surface pressure, which represents an invalid test. Therefore, the clamping force of the coil springs was adjusted to be between 1 and 2 N. For this setup, no crack initiation was observed from this artificial notch and slippage of the extensometer is prevented too. Compared to Cyan-Acrylat-adhesive as used in [11] for the mounting of the extensometer, the preparation time for each fatigue test is significantly reduced by just using tension springs without additional glue.

Another factor influencing buckling is the overlap between the buckling support and the specimen. Here, only the smallest possible area of the specimen must be exposed as a contact surface for the knife edges of the extensometer. Otherwise, local instability failure will occur at the protruding area of the specimen. Especially with higher compressive loads or strains, this is an issue that becomes prevalent.

4.1. Tightening torque

The tightening torque of the screws indirectly influences the measurement data and should be defined for reasons of comparability and to ensure an evenly distributed contact pressure. However, the specification of a proper tightening torque has a conflict of objectives. On the one hand, too low preload forces (as well as a low stiffness of the support system) can result in unintended movement of the whole anti-buckling restraint. Furthermore, low preload forces can cause the bolted joint to loosen during the fatigue test and therefore, reduce the tolerable buckling load under compression. On the other hand, the influence on the measurements increases with increasing pre-tensioning force due to higher friction. The effect of the tightening torque on force is plotted in Fig. 5. The experimentally measured force without anti-buckling support (equal to 0 Nm) serves as a reference. Compared to the reference, the required force to achieve the same elongation of the material is approximately 3% higher with a tightening torque of 0.12 Nm. Thus, the anti-buckling restraint can have a noticeable effect on the fatigue life.



Fig. 5. Experimentally determined force to obtain a predefined displacement in the elastic regime of the material without (0 Nm) and with anti-buckling restraint (PTFE foil) for different torque values.

4.2. Friction reduction system

The use of an anti-buckling restraint creates a sliding contact between the anti-buckling-device and the specimen. To limit the amount of friction, some form of friction reduction system can be used between those two components. Therefore, six different coating types are investigated: four polymer foils and two diamond-like carbon (DLC) coatings, whereby for the DLC coatings only the roughness of the base material is varied. The polymer foils are cut out according to the shape of the buckling support and adhered to it, whereas the DLC coating is entirely applied by the coating process. The friction is measured by oscillating a segment of an electrical sheet on a flat half of the anti-buckling restraint, which is mounted inside the tribometer. The corresponding coefficients of sliding friction in dependence of normal load are shown in Fig. 6.

The selected loads correspond to the screw preload forces which result from the torque values as described in chapter 4.1. The Polyethylenimine (PEI) foil exhibits the highest friction values, while Polytetrafluoroethylene (PTFE) foils shows the lowest friction, independent of its thickness. The usage of DLC coatings lead to slightly higher friction than PTFE foil, whereby the polished substrate surface provides less friction compared to the as-rolled surface condition. The coefficient of friction of the investigated Polypropylene (PP) foil is in the range of DLC coating.

4.3. Influence of the anti-buckling device

After the analysis of the tightening torque and coating system, a numerical simulation is performed to assess the influence of the antibuckling restraint on the experimental results. The electrical steel sheet specimen (Type V) is considered under force- and displacementcontrolled tensile loading for three different test setups. The setup without the use of an anti-buckling restraint serves as reference and is compared to the setup with a DLC coating and the setup with a thin PTFE-foil. The tightening torque is set to a constant value of 0.06 Nm by utilizing a fine torque wrench. In Fig. 7 a), the corresponding simulation setup is presented. The material behavior of the two halves of the antibuckling restraint, screw connection and PTFE-foil is assumed as linearelastic. For the electrical steel sheet specimen, nonlinear elastic-plastic material behavior according to the monotonic material properties, see Table 2, is applied. The sliding contact between the two halves of the anti-buckling device and the specimen are modeled as surface-to-surface contact and a penalty friction formulation. For the DLC coating, the coefficient of friction is set to 0.23 and for the thin PTFE-foil to 0.18. In the first step of the simulation, the bolt preload is defined and the



Fig. 6. Coefficients of sliding friction for different coatings and loads.



Fig. 7. Influence of the anti-buckling restraint on the stress distribution in the nominal cross-section, a) simulation setup, b) under force- and displacement-control.

contact between anti-buckling restraint and specimen is established. In order to apply the bolt preload, the given tightening torque must be converted into an equivalent preload force. Based on a bolt preload calculation, an equivalent preload force of 52.5 N is determined for each screw. After that, the tensile loading is applied at the upper head of the specimen. For the force-controlled simulation, a tensile force of 1350 N, which corresponds to a nominal stress of 500 MPa, is specified. In the case of displacement-control, a displacement of 0.25 mm is used. For the evaluation of the influence of the anti-buckling restraint, the stress distribution in the nominal cross-section of the specimen is analyzed for the three different test setups. Under force-control, the von Mises equivalent stress standardized to the nominal stress is about 3–4% smaller when the anti-buckling restraint is used, see Fig. 7 b).

Due to the tightening of the anti-buckling restraint on the specimen, a certain amount of the loading is transferred into the anti-buckling restraint. The magnitude of the force transmission is principally dependent on the coefficient of friction. Since the coefficient of friction of the PTFE-foil is smaller compared to the DLC coating, the transferred force is lower, as well. Besides the lower equivalent stress level, the stress distribution in the nominal cross-section seems not to be influenced by the anti-buckling restraint. The stress curves only show a slight distortion due to the unsymmetrical design of the anti-buckling restraint, which is necessary for the mounting of the extensometer.

In contrast to the force-controlled loading, the anti-buckling restraint has a significant smaller influence on the stress distribution under displacement-control, see right y-axis in Fig. 7 b). To ensure a constant displacement, more force is required to compensate the force transmission into the anti-buckling restraint. This allows for approximately the same averaged von Mises equivalent stress in the nominal crosssection of the specimen. However, it should be noted that the stress curves show a slightly increased stress gradient, when the anti-buckling restraint is used. Again, the stress distributions are unsymmetrical to some extent due to the design of the anti-buckling restraint. The choice of the coating system, more specifically the magnitude of the coefficient of friction, becomes less important under displacement-control.

4.4. Test setup details for fatigue tests with compressive forces

LCF tests are typically performed in strain control mode and under fully reversed loading. Consequently, for testing thin electrical steel sheets, buckling in the compressive half-cycle must be considered, as

this elastic or plastic buckling influences the cyclic deformation behavior and the fatigue life. Exemplary hysteresis curves for different test conditions illustrate such an influence on the cyclic deformation behavior in Fig. 8. Depending on the configuration, the hysteresis shape can be influenced by friction and buckling. Buckling for example can result from a high resilience of the coating system or if the stiffness of the anti-buckling restraint is too low. The recommendation for the test setup of international standards proves to be disadvantageous for testing thin electrical steel sheets, as the specified thickness of the recommended PTFE foil is defined as 1.0 mm [13], which is several times thicker than the electrical steel sheet itself. The low elastic modulus of the thick PTFE foil in combination with high compressive loads can cause waviness of the specimen due to microscopic buckling. If the stiffness of the buckling support, coating system, or the screw connection is way too low, it can manifest itself more clearly in macroscopic buckling, which leads to a bulky and misshapen hysteresis curve, see Fig. 8. After the cyclic test, macroscopic buckling is indicated by a high waviness of the samples. In contrast to macroscopic buckling, waviness from microscopic buckling is only very slight and barely visible. Nevertheless, any waviness should be reduced, as it can disturb the cyclic deformation behavior. Specimens that show waviness after the fatigue test tend to reach fewer cycles to failure.

High friction can occur either from high contact pressures, resulting from improper torque values, or due to high friction caused by the tribological system of specimen and anti-buckling restraint. Both can lead to slight changes in hysteresis shape, as indicated in Fig. 8. As a consequence of high friction, higher forces are needed to achieve the defined strain amplitude. However, this additional force is completely induced into the anti-buckling restraint in the case of strain-controlled fatigue tests. Therefore, no significant influence on fatigue life is observed for this control mode despite the different hysteresis shape. On the other hand, stress-controlled fatigue tests with a high friction setup are not recommended as the higher friction leads to part of the applied force to be derived into the anti-buckling restraint as friction, see chapter 4.3. As a result, the number of cycles to failure increases artificially.

Ideal hysteresis curves with low friction and buckling are achieved by using very thin PTFE foils and stiff anti-buckling restraints, indicated by the green line in Fig. 8.

5. Discussion

5.1. Specimen geometry

The validity of HCF and LCF tests depends to a large extent on the volume of the material that has been subjected to homogeneous cyclic deformation. In an hourglass specimen (Type III) the volume of material with a homogenous stress state is very small and the significance of the data obtained remains questionable. This problem is much more acute when the data determined is related to a material that is prone to failure from defects [25]. Because electrical steel sheets belong to this category of material, the design of an area with an approximately homogeneous stress distribution is important. The probability for the presence of defects and unfavorably oriented grain colonies is highest for type V. Consequently, this variant also shows the highest scattering. Another important criterion of a specimen geometry for fatigue testing is a low stress concentration factor. Type V provides the lowest stress concentration factor of all investigated variants and crack initiation can occur depending on local defects or uncertainties rather than depending on overlaying geometrical influences. However, to achieve this, the overall length of the loaded section must be longer, which results in less buckling resistance. Nevertheless, the difference in buckling resistance is small and can be compensated by a stiff anti-buckling restraint. Therefore, type V appears to be a suitable compromise between maximizing the stressed volume, high accuracy of strain measurement, reducing the concentration factor and simultaneously maintaining proper stability in



Fig. 8. Stress-strain hysteresis loops under symmetric strain-control mode with influences on hysteresis shape due to test setup and its coating system.

compression.

5.2. Test setup

In general, the weight of the anti-buckling restraint should be as low as possible, as it is mounted in a floating manner and its weight influences the required torque of the screws. However, the stiffness should be high enough to resist buckling when fatigue tests are performed with high compressive loads. Consequently, it is a preferable scenario to use two more bolts in the center, which additionally stiffens the critical area for buckling. Using four screws instead of six screws would increase the required bolt preload force of the remaining four screws as well as the required thickness of the anti-buckling support. Recommendations based on the test parameters to be considered are listed in Table 4. The overview includes different load conditions with the recommended antibuckling restraint, coating system, and tightening torque. The geometrical design and the given parameters are optimized for specimen type V. In the case of a different specimen geometry with a shorter length than type V, it may be possible to achieve adequate results without the additional two screws in the center.

Buckling is particularly problematic at high strain amplitudes $\Delta \varepsilon_A > 0.5\%$. DLC coatings are only a few micrometers thick and offer the highest stiffness of all investigated coatings and should therefore be used for strain-controlled fatigue tests with high strain amplitudes. For other load conditions, DLC coatings are disadvantageous, as friction is higher and slight wear over the course of many fatigue tests can change the topography of the anti-buckling restraint. Therefore, the condition of the restraint should be checked before each test. Although the wear rate is low, even at high cycle rates, the influence of a changing topography by the DLC layer over time is difficult to quantify. Thus, DLC coatings should be avoided for fatigue tests in the high cycle regime. At high strain amplitudes, on the other hand, the expected number of cycles to failure is low, which is why the recommendation for DLC coatings in combination with the two additional central bolts is only made at high

Table 4

Overview of different load conditions with the recommended test concepts, coating system, and tightening torque (specimen type V).



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strain amplitudes.

The recommendation of ISO 12106 is not suitable for thin electrical sheets because the PTFE foil described there should have a thickness of 1 mm [13]. Since PTFE is a soft material, micro-buckling, i.e. a slight waviness, can occur as a result of the elastic flexibility of the PTFE foil. Therefore, the thinnest possible PTFE foils should be used in order to minimize micro-buckling. A foil thickness of 0.13 mm proved to be suitable for this purpose, and this type of foil is commercially easily available.

In strain control, strain ratios deviating from -1 are not recommended due to cyclic relaxation of the mean stress, which is comparatively high for electrical steel sheets and tending toward a mean stress of zero. As a consequence of the cyclic relaxation, even for strain ratios above 0.1, compression forces are not prevented in the lower part of the hysteresis loop [11,13]. However, if such experiments are planned, the usage of an anti-buckling restraint is mandatory, but the requirements for stiffness are lower as for symmetric strain-controlled fatigue tests. Therefore, thin PTFE foils are recommended for this application.

6. Conclusion

The current work aims to propose solutions for challenges in the context of electrical steel sheet testing. The issue of buckling during the compressive part of cyclic axial loading can be controlled by antibuckling restraints. The geometrical design of the anti-buckling device, the coating system and the tightening torques can influence the hysteresis shape and fatigue life. The combined experimental and numerical work presented here proposes several test setups depending on the desired test parameters. The described measures can reduce the tendency for buckling and can limit die influence of the test setup on the experimental results.

The comparison of different specimen geometries for fatigue testing of thin electrical steel sheets shows its influence on fatigue life. As the use of an anti-buckling restraint allows only the wavy buckling mode, the buckling resistance of the sample becomes less critical with the proposed test setups. Consequently, the length of the specimen can be higher and thus, the design of the gage-to-grip transition region can focus on a low stress concentration factor.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Albin Gottwalt reports financial support was provided by Federal Ministry of Education and Research (BMBF) and the AUDI AG.].

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