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Abstract

Destructive micrograph analysis (MA) is the standard method for the assessment of clinched joints. However, during the joint preparation for the MA, geometric features of the joint can change due to elastic effects and closing cracks. X-ray computed tomography (CT) is a promising alternative to investigate the joint non-destructively. However, if the material properties of similar joining partners are the same, the CT is not able to correctly resolve surfaces in the joint that are close to or pressing onto each other. These surfaces are relevant for the determination of characteristic dimensions such as neck thickness and undercut. By placing a thin, highly radiopaque tin layer between the joining partners, the interfacial area in the reconstructed volume can be highlighted. In this work, a method for the localisation of the tin layer inside the joint as well as threshold value procedures for the outer joint contour in cross section images are investigated. The measured characteristic dimensions are compared with measured values from MA of the same samples and of samples without tin layer. In addition, possible effects of the tin layer on the joining point characteristics as well as problems of the MA are discussed.

1 Introduction

Processing time and costs are critical factors in the manufacturing industry. Clinching according to DIN 8593-5:2003-09 is a mechanical joining process which joins sheet metals by forming [1].

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[*]Other people who contributed to this document include Gunnar Henke (Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden), who prepared the joining samples with tin layer, Till Kremonke (Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden), who prepared the samples for microscopy, Helmut Gerschütz (Chair of Manufacturing Metrology (FMT), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), who performed the micrograph analysis and Max Böhnke (Laboratory for Material and Joining Technology, University of Paderborn, who provided the measured data of his results published in [5] on joint samples without tin layer.).

[†]contributed data curation, formal analysis, investigation, methodology, software, validation, visualization, and writing (the original draft) and lead the review and editing process.

[‡]contributed investigation and writing and supported the review and editing process.

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[**]contributed to conceptualization, funding acquisition, project administration and supervision.

Thereby, a form fit is created without any cutting securing it against unwanted loosening. Thus, this fast method of joint production is becoming increasingly important. During the forming process, a form fit is achieved by forming an undercut f^* (Figure 1) using a punch and die. Together with neck thickness $t_n{}^*$, bottom thickness $t_b{}^*$ and die side bottom thickness $t_{b2}{}^*$, this forms the characteristic dimensions of a clinched joint [3].
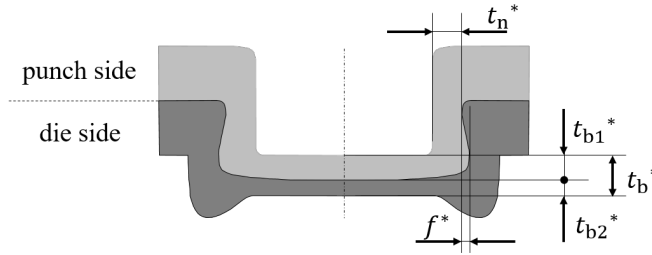

Figure 1: Selected characteristic dimensions of a clinched joint [3]

The versatile character of a clinched joint requires a consistent understanding of the joining systems along the entire process chain and a variety of testing techniques to characterise the materials, joining processes and components [12]. Usually, these characteristic dimensions and damage phenomena like cracks, which limit a clinch point's strength, are detected in destructive micrograph analyses (MA) [7]. This requires complex preparation and destroys the sample. However, with this method, only one up to a maximum of two cutting slices of the joint can be investigated and this testing method cannot detect elastic deformations that reset during specimen preparation for the MA. Assumptions are therefore usually based on a small number of experimental studies and expert knowledge [8]. Industrial X-ray computed tomography (CT) has the potential to examine clinched joineds non-destructively by creating a volumetric image and by generating a large number of sectional images along the rotationally symmetrical axis of the joint. Moreover, this method can in principle be applied in in-situ investigations, which would also allow the detection of elastic deformations and cracks that reset after unloading. The relevance of joint examinations by CT has been proven many times [9][13][14]. The measurement chain for CT measurements is shown in Figure 2.
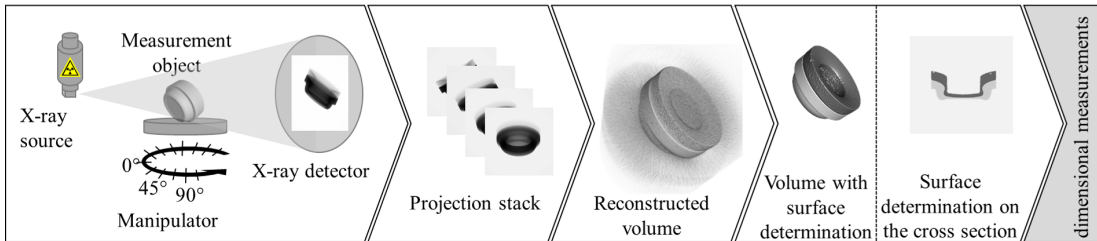

Figure 2: Measurement chain for dimensional CT measurements

In a CT scan, a measuring object is placed between the X-ray source and detector on a positioning unit and is then scanned at different angles over 360°. The X-ray radiation is attenuated by the measuring object depending on the component thickness and material properties. The residual radiation is converted into an electrical signal by each pixel of the detector and integrated so that a projection is produced for each angular position. In a reconstruction pro-

cess, the projections are transferred into a three-dimensional volume, where the grey values of the individual voxels (volume pixels) approximately represent the amount of absorbed radiation at the respective location. For dimensional metrology, a subsequent determination of the surfaces is essential. This is usually done on the basis of a single threshold value that separates the component from the background. Describing the damages and accurately measuring the characteristic dimensions in CT, poses some challenges if the joining partners have the same material and thus the same X-ray absorption properties. If the sheets are pressed onto each other, the interface between the sheets cannot be detected because of the limited spatial and structural resolution of conventional CT. The poor contrast between sheet and interface prevents their use as starting points for measuring the characteristic dimensions. Furthermore, at some points, partial metallic bonding occurs [11]. Consequently, the interface is not visible in the CT scan making the measurement of the undercut or the neck thickness impossible.

Therefore, this paper presents an approach for determining the characteristic dimensions of clinched joints with CT by placing a high absorption intermediate layer made of tin in between the metal sheets. The joining partners can be distinguished from each other because of the resulting increased contrast between layer and sheet observable in the measurement data. Because of the high mechanical forces in the clinch point, a further thinning of the tin sheet can be expected below the voxel size of the CT measurement. However, due to the partial volume effect, details smaller than a voxel size can be detected due to its different absorption properties [2]. Regardless of the mechanical load on the tin foil between the sheets to be clinched, this should be recognised. Due to systematic measurement deviations in CT measurements, an exact determination of the layer thickness is not possible. The localization of the intermediate layer is inferred by a local evaluation of the grey value on the interpolated cross section image in the reconstructed volume. The surface determination is carried out on the basis of these section plane. Schromm et al. demonstrated a methodology for creating 2D cross-sectional images of joining elements from CT volumes – an important step for quality and geometrical analysis [15]. The dimensions of the characteristic quality values of the clinched joints derived from the sectional images are compared with results from MA and outside micrometre measurement in order to quantify the geometrical influence of the preparation for MA.

2   Methodical Approach

2.1   Preparation of clinched joints with intermediate layer

Six clinched joints were produced. For this purpose, circular blanks with a diameter of 40 mm and a thickness of 2 mm made of aluminium (EN AW 6014) are used. A tin foil with a diameter of 14 mm and a thickness of 10 µm was inserted as a layer between the blanks. The tool combination used was a tapered conical punch with 5 mm diameter (A50100*) and a die with 8 mm diameter (BE8012) (both from TOX PRESSOTECHNIK GmbH & Co.KG, Weingarten, Germany). The joining force was 33.1 kN. The partial volume effect for detectability of the intermediate layer in CT is achieved by the higher density of tin of 7.31 g/cm^3 compared to aluminium with 2.7 g/cm^3. The stronger mass attenuation (compare Figure 3a and Figure 3b) can also be explained by the higher atomic number in the periodic table of the elements, where tin is found at position 50 and aluminium at position 13. The higher the atomic number, the stronger the photoelectric effect and therefore the X-ray absorption characteristics of the material [10].
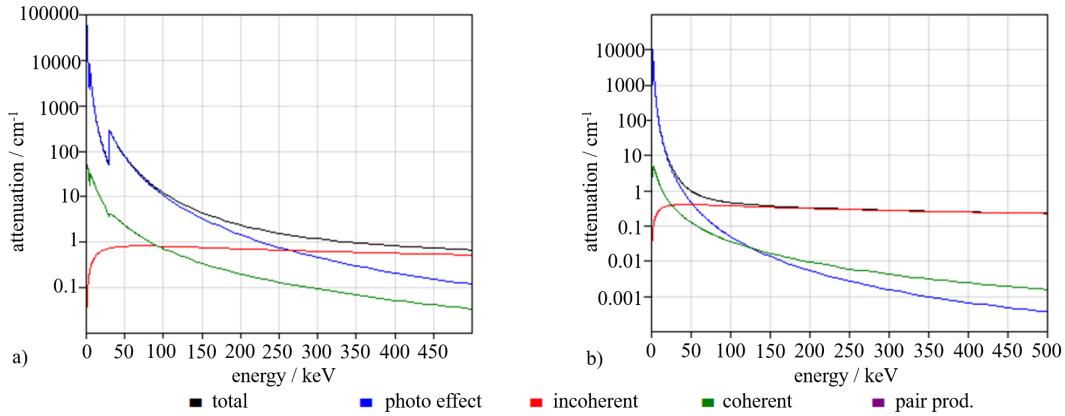
Figure 3: Comparison of the attenuation of tin (Sn) (a) and aluminium (Al) (b) (created with artist (Bundesinstitut für Materialforschung))

2.2   Computed tomography-based dimensional analysis

The CT measurements are realised with the measuring system Metrotom 1500 (from Carl Zeiss AG, Oberkochen, Germany). Each clinch specimen was tilted by approx. 30° during the measurement. Each measurement was taken at 150 kV and 66 µA with a resulting spot size of 7 µm. Over 360°, 2050 radiographic projections of the specimen are taken, each was averaged from 3 images. The integration time was 2000 ms and the detector signal was amplified 16 times. With regard to the positioning of the test specimen, a voxel size of 8.76 µm was achieved. A prefilter of 0.25 mm copper was used to harden the X-ray spectrum. For the generation of sectional images, a surface of the test specimen was determined on the basis of the measurement data with the software VGStudio Max (version 3.5.2). By adjusting a conical frustum on the punch side, the measurement data are vertically oriented on its axis of rotation. Ideally, the axis of rotation is perpendicular to the die side face of the clinched joint. Using this axis of rotation and the interpolated imaging of the reconstructed volume, sectional views were created at 4 positions (0°, 45°, 90° and 135°). The image resolution is 2092 pixels x 1269 pixels and about 16 mm x 8 mm of the clinch specimen is visible. To determine the size per pixel and the characteristic dimensions of the clinch specimens, the sectional images are imported with a 1.5 mm ratio scale present in the sectional image of VGStudio into the numeric computing environment MATLAB (The MathWorks, Inc., Natick, USA). For each sectional image, the two neck thicknesses, the two undercuts as well as the bottom thickness and die side bottom thickness were evaluated. The procedure for each characteristic dimension is roughly divided into 4 steps (see Figure 4). First, a rectangular area is selected that contains the characteristic attribute. This is followed by the localisation of the tin interface. In order to generate measuring points on the component surface, the aluminium surface is determined. Finally, the characteristic dimension is calculated. For the determination of the interface, the maximum grey value within a row or column (depending on the characteristic value) is determined. In the bottom area, outliers with more than three scaled median absolute deviations away from the median are automatically removed. When further obvious outliers appear, they are removed manually. The aluminium surface of the component is influenced by artefacts due to the multi-material characteristics of the clinched joints and the fact of an incomplete mapping due to the high magnification of the

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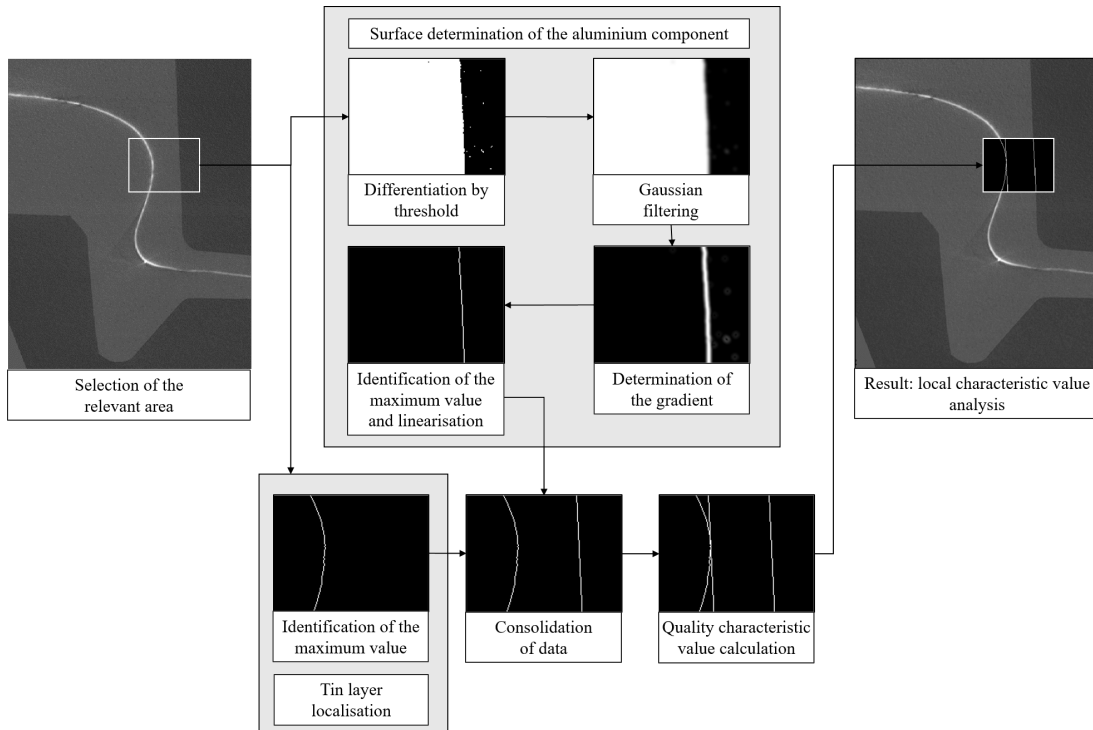specimens with included joining point on the detector.

Figure 4: Procedure for determining the neck thickness of a clinched joint in a sectional CT image.

In the first step based on the sectional image, a grey scale histogram was created. Component and background are represented by intersecting characteristic grey value distributions. The intersection point (valley) was used as the grey value threshold. This step has a high influence on the geometric values of the characteristic dimensions that are measured from the aluminium surface [16] (see Figure 5). While the bottom thickness is a classical bidirectional measure, the die side bottom thickness and the neck thickness are atypical measures with both unidirectional and bidirectional character [4]. The undercut is a typical unidirectional dimension and therefore independent of surface determination and threshold definition.

The value 0 is assigned to the background and the value 1 to the component. Subsequently, the area was filtered with a 2-D Gaussian smoothing kernel with twice the standard deviation. Then the calculation of a gradient image is performed. Then, as with the interface, the largest value within a row/column is determined. Subsequently, outliers were removed which are more than three scaled median absolute deviations away from the median. Straight compensation lines were fitted to the clinch point edges facing towards the punch's lateral side and edges facing to the anvil of the die (compare Figure 1). There are small bumps on the anvil of the die which are visible on the respective surface of the clinch point. These bumps were removed manually and not taken into account in the fitting process. With these procedures all contours for the determination of the characteristic dimensions are available. Thus characteristic dimensions were determined according to [3]. For the neck thickness and the residual bottom thickness, the shortest distance of the calculated compensation line to the pixels representing the tin layer
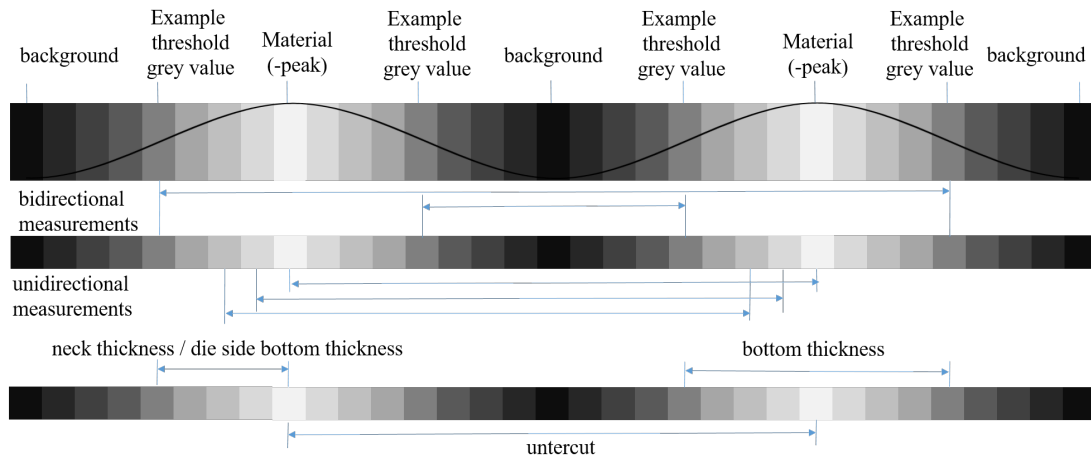
Figure 5: Schematic geometric dependence of measured values after threshold value definition. Bidirectional (grey value dependent) measured values: bottom thickness; Unidirectional (grey value independent) measured values: undercut; Measured values with uni- and bidirectional character: neck thickness and die side bottom thickness

was calculated, which represents the characteristic dimension. The undercut was determined by means of a group of straight lines which pass through a pixel representing the tin layer and which are perpendicular to the surface/straight line on the die side. Here, the largest distance between 2 straight lines represents the characteristic dimension. The bottom thickness was calculated using the smallest distance between the described maximum values in the punch front edge and the line fitted to the die side. The process of determining the characteristic values is shown in 4 as an example for the neck thickness. In addition to the MATLAB-based determination of characteristic dimensions, comparative measurements were carried out on the CT device FCTS 160 - IS (from Finetec FineFocus Technologies GmbH, Garbsen, Germany) where the samples are positioned vertically. The used X-ray source parameters were 150 kV and 50 µA. Each of the 1440 projections were recorded at an integration time of 1250 ms by the detector. The spectrum was pre-filtered with 0.1 mm copper and a voxel size of 4.68 µm was achieved. The characteristic dimensions of the joint were also determined on the basis of sectional views of the reconstructed volume, but with the intuitive use of the measuring software VGStudio Max (Version 2.2.6).

2.3   Micrograph analysis

For comparison of the values measured by CT with those of the MA, the samples were cut into quadratic shapes (Figure 6a). A range of 20 mm diameter starting from the centre of the joint was not trimmed. The cut samples were then embedded in epoxy resin (Figure 6b and Figure 6c). Finally, three grinding and three polishing processes were performed until the middle plane with maximum clinch diameter required for microscopy was reached (Figure 6d). In three of the six samples this plane was not met. Microscopy was realised on the Werth VideoCheck-IP250 multi-sensor coordinate measuring machine using a telephoto lens with a working distance of 100 mm in bright field with lighting setting at 10 %. No noticeable difference in the characteristic dimensions was found when the bright field was varied between

10 % and 25 %. At the selected setting, a black gap of approx. 15 µm - 30 µm is visible between the joining partners (Figure 9c). This gap is added to the thickness of the neck, the undercut and the bottom thickness on the die side, each with half the thickness. Furthermore, before the MA, the residual bottom thickness of the samples with tin layer is measured with an U-bolt micrometer for thread measurements with a one-sided pointed thread measuring insert, which was placed centrally on the punch side (U-bolt micrometer).
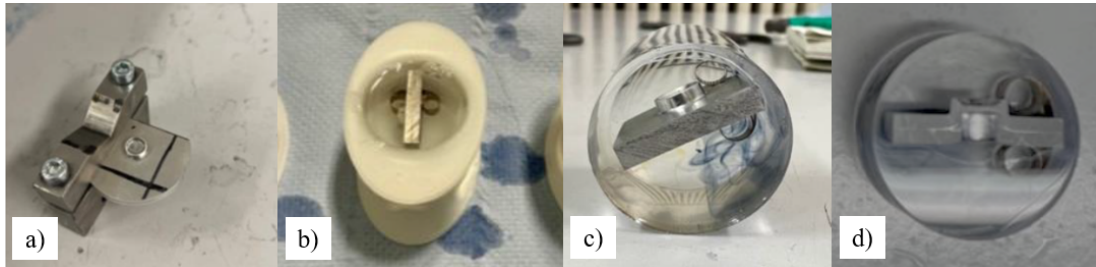

Figure 6: Preparation of the joint for the MA: Cutting (a); Embedding in epoxy resin (b) (c); Sample after grinding (d)

3   Results and Discussion

With the addition of the tin layer, the individual joining partners can now be differentiated at the two boundary surfaces despite of the same material and X-ray absorption properties (Figure 7). The process-related shaping of the inlaid tin layer is clearly visible in the CT scan. The tin layer is slightly torn in some places, but this does not affect the evaluation negatively.
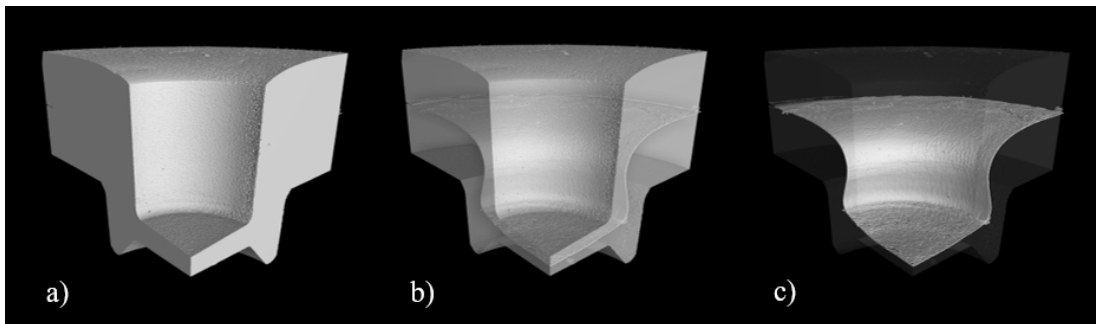

Figure 7: Partial section of a clinch point in the CT. a) Total volume; b) Segmented materials; c) Formed tin layer.

Figure 8 shows the results for each characteristic dimension with a boxplot for each measurement method. The boxplot contains the median (separation line of the boxes), mean value (cross), the interquartile range (box above and below the median, each with 25 % of the measurement values), the maximum range (whiskers drawn within the 1.0 interquartile range value) and outliers. The number of measurements on a single sample realised with the respective measurement method is given. In addition, the measurement results published in [5] of a micrograph

analysis of the joint created under the same conditions without a tin layer are shown (MA without Sn).

In the case of the values for the **bottom thickness** (Figure 8a), the MATLAB-based evaluation (approx. 0.62 mm – 0.65 mm) with 24 measured values and low scatter shows a high level of agreement with the values of the U-bolt micrometer (approx. 0.64 mm - 0.66 mm), which is assumed to be particularly trustworthy. The concerns expressed in [6] regarding bidirectional measurement on surfaces defined with a global threshold, which were also investigated in [16], cannot be confirmed for this application. The scatter of the VGStudio-based variant is also low, but there is only little overlap in the measured values (approx. 0.60 mm – 0.63 mm). The results of the microsection examinations are more scattered. They are in a similar range (approx. 0.67 mm – 0.74 mm), but do not agree with the values of the U-bolt micrometer. For the **die side bottom thickness** (Figure 8b), there is a high agreement in the measured values for the CT based methods (approx. 0.31 mm – 0.35 mm). The MA-based variants scatter comparatively strongly with values from 0.31 mm to 0.43 mm. Here the addition of half of the gap thickness to the measurement also supports the high deviation to the other measurement methods. A positive aspect is the median, which is approximately 0.33 mm for all methods. For the **undercut** (Figure 8c), the measured values of all methods scatter strongly. Values between 0.21 mm and 0.34 mm exist. In the MATLAB-based evaluation, double tin layers are often seen in the undercut area (Figure 9a). A possible, but unlikely cause is insufficient fixation of the joint during the measuring process. It is considered more likely that restoring forces have occurred in the joining point and that the soft tin layer in the gap leaves residues on both surfaces. A sectional image obtained under unfavourable microscopy settings of 40 % in the dark field, in which the tin layer can be traced, supports this hypothesis (Figure 9b). As already indicated, similar problems also occur with the micrograph analysis. Here, the joining partners are optically separated from each other by a black line which is approx. 15 µm to 30 µm thick (Figure 9c). In addition to the restoring forces already mentioned, the gap may also have been caused by the relief during micrograph preparation despite the embedding in epoxy resin. Another possible cause that can be mentioned is the favouring of scattering of the undercut values solely due to the presence of the elastic tin layer and their possible influence on friction behaviour and shaping. The mechanisms at this point can be diverse. However, it can be assumed that the tin layer prevents the material closure described in [11]. Only the median value of the MATLAB-based CT and the median values of the micrograph analyses are close to each other at approx. 0.29 mm. The phenomena described for the undercut also occur in the area of the **neck thickness** for the samples with tin layer. Here, all measurement methods scatter similarly strongly (Figure 8d). The interquartile ranges are also similar (approx. 50 µm), although at different positions. The measured values on reference samples without a tin layer are largely in a different range.

In general, it can be said for the MATLAB-based CT evaluation that the interquartile ranges are smaller due to the higher number of measured values and their possible Gaussian distribution. The median and mean values are close to each other and the distribution is lower overall. When preparing the specimens for the MA analysis, it is possible that the specimens are not exactly grinded to the symmetry plane. Consequently, this can lead to the widening of a gap or the tin layer. Also, the characteristic dimensions of the joint are larger, which can be seen in the following comparison. An evaluation of the samples with correctly recorded microscopy plane is shown in the boxplots in Figure 8e-h. For the micrograph analysis, the scatter of the measured values is reduced compared to the MA analysis with all samples. The
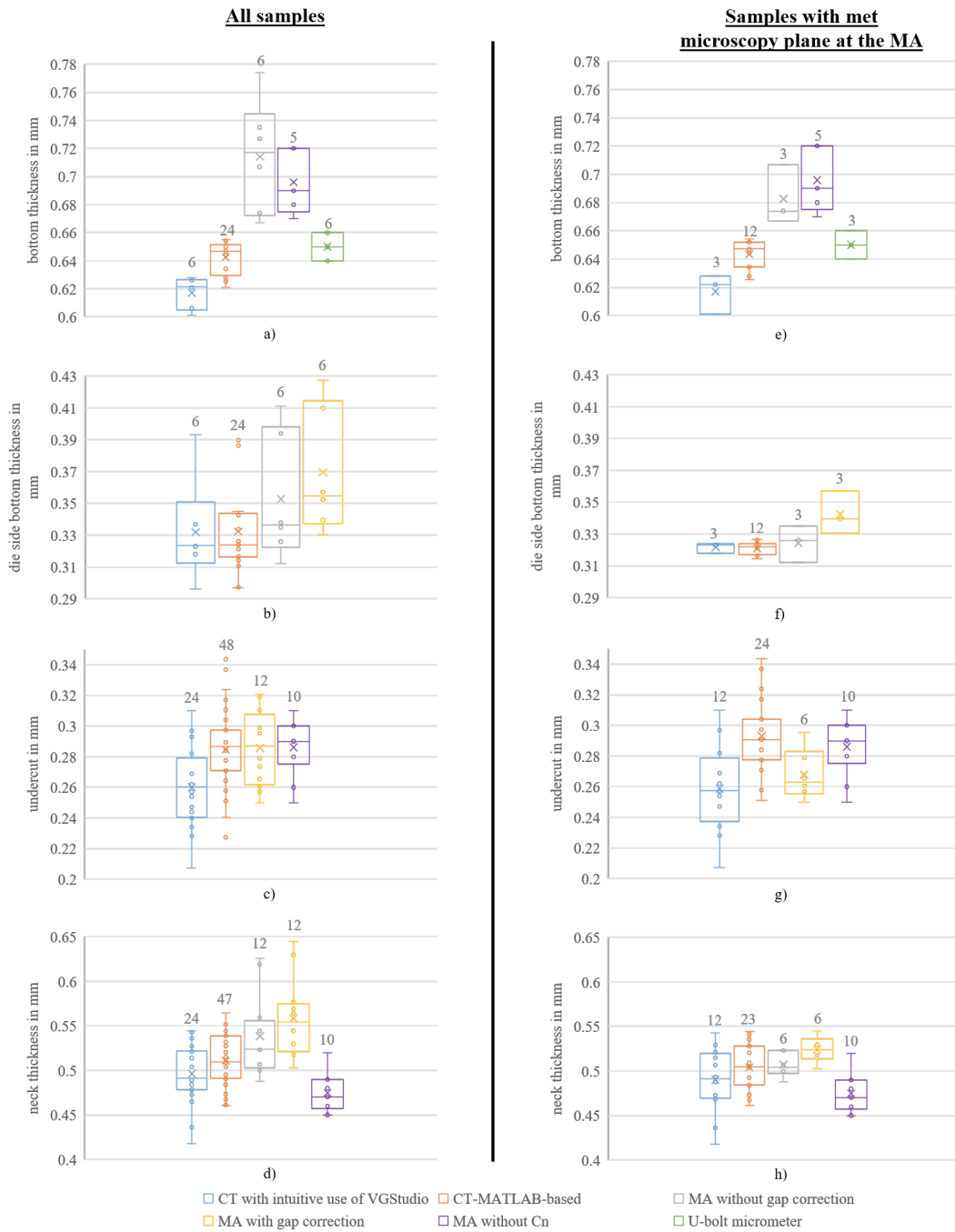
Figure 8: Comparison of the determined characteristic dimensions of clinched joints depending on the method used. The scope of measurement is indicated above each boxplot.
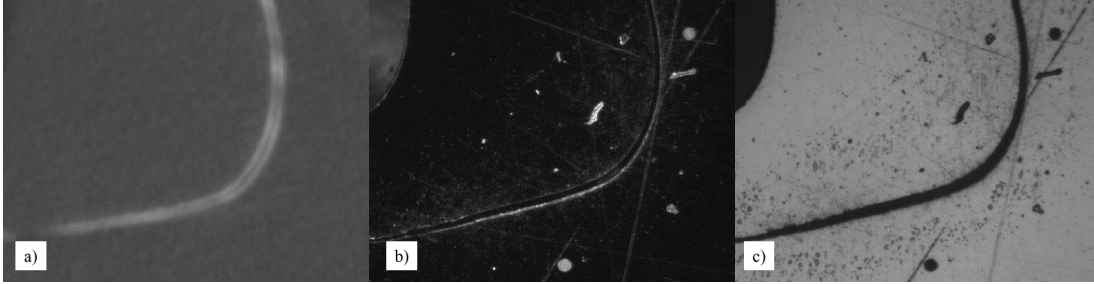
Figure 9:   Section of a joint depending on the imaging used: CT slice images with visible double lines (a); Microscopy at 40 % in dark field with tin layer appearing brighter (b); Microscopy at 10 % in bright field with a gap or line width of approx. 15 µm - 30 µm

values of the measurement methods not concluded from the MA change only slightly due to a possible normal distribution. The values of the bottom thickness (Figure 8e) scatter less into the thicker range, thus the median decreases (approx. 0.67 mm). The values for the die side bottom thickness (Figure 8f) also decrease from a span of 0.10 mm to 0.03 mm and the values are distributed more evenly to both sides. For the undercut area, the median falls outside the previously uniform level (Figure 8g). For the neck thickness, there is a high agreement between the uncorrected values of the micrograph analysis and the MATLAB-based evaluation (Figure 8h).

4   Conclusions

The quality of clinched joints was evaluated according to the state of the art by the destructive method of MA, although CT could provide a non-destructive alternative. However, conventional CT is not able to distinguish between similar joining partners that are pressed onto each other as it occurs in the clinched joint. In this work it was shown that by means of a high X-ray absorbing tin sheet, joining partners made of the same material can be separated in a way that allows a non-destructive measurement of their internal characteristic dimensions. However, analysing the data an influence of the intermediate layer on the geometric properties of the joint cannot be excluded. Nevertheless, weaknesses of the micrograph analysis also became apparent, for which the CT-based evaluation with the high number of measured values represents an appropriate alternative. In conclusion, it can be noted that the CT-MATLAB-based evaluation delivers better results than the intuitive VG Studio evaluation in grey-scale images without segmentation. But the measured value scatter caused by the joining process seems to be high for the samples and the additional effort cannot always be justified in practice by the slightly better measurement results of the CT-MATLAB-based evaluation.

5   Acknowledgments

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