Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 1489-1497
doi:10.4028/p-32330d

Submitted: 2021-12-07
Revised: 2022-01-28
Accepted: 2022-02-10
Online: 2022-07-22

Investigations on Combined *In-Situ* CT and Acoustic Analysis during Clinching

Daniel Köhler[1,a*], Richard Stephan[2,b], Robert Kupfer[1,c], Juliane Troschitz[1,d], Alexander Brosius[2,e] and Maik Gude.[1,f]

[1]Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden, Germany

[2]Chair of Forming and Machining Processes, Technische Universität Dresden, Germany

[a]daniel.koehler3@tu-dresden.de, [b]richard.stephan@tu-dresden.de, [c]robert.kupfer@tu-dresden.de, [d]juliane.troschitz@tu-dresden.de, [e]alexander.brosius@tu-dresden.de, maik.gude@tu-dresden.de[f]

Keywords: X-ray; Clinching; Process monitoring; Active acoustic testing

Abstract. Clinching is a cost efficient method for joining components in series production. To assure the clinch point's quality, the force displacement curve during clinching or the bottom thickness are monitored. The most significant geometrical characteristics of the clinch point, neck thickness and undercut, are usually tested destructively by microsectioning. However, micrograph preparation goes ahead with a resetting of elastic deformations and crack-closing after unloading. To generate a comprehensive knowledge of the clinch point's inner geometry under load, in-situ computed tomography (CT) and acoustic testing (TDA) can be combined. While the TDA is highly sensitive to the inner state of the clinch point, it could detect critical events like crack development during loading. If such events are indicated, the loading process is stopped and a stepped in-situ CT of the following crack and deformation development is performed. In this paper, the concept is applied to the process of clinching itself, providing a detailed three-dimensional insight in the development of the joining zone. A test set-up is used which allows a stepwise clinching of two aluminium sheets EN AW 6014. Furthermore, this set-up is positioned within a CT system. In order to minimize X-ray absorption, a beryllium cylinder is used within the set-up frame and clinching tools are made from Si3N4. The actuator and sensor necessary for the TDA are integrated in the set-up. In regular process steps, the clinching process is interrupted in order to perform a TDA and a CT scan. In order to enhance the visibility of the interface, a thin tin layer is positioned between the sheets prior clinching. It is shown, that the test-set up allows a monitoring of the dynamic behaviour of the specimen during clinching while the CT scans visualize the inner geometry and material flow non-destructively.

Introduction

Especially in the automotive industry, there is an increase of components with various materials resulting in a demand for cost efficient joining technologies. Clinching is a joining method that creates joint by locally pressing two join partners into a die without any particular surface preparation and heat input. Thus this force- and form-fit [1] and cost efficient joint [2] is receiving increased attention recently.

Usually, the clinching process is monitored with the window technique [3], observing the force-displacement-curves of the clinching tool during joining. This provides general quality information but no detailed data on the inner joint geometry. Furthermore, geometric characteristics such as bottom thickness, undercut and neck thickness can be evaluated in destructive microsections or using the outside micrometre [1]. There are some disadvantages inherent to these methods: Firstly, the specimen preparation is costly and time consuming. Secondly, drawing conclusions from the force-displacement measurement to the local material structure and clinch point geometry is limited. Finally, the deformation and damage chronology is not consistently given. In addition, elastic deformations and cracks that close after unloading cannot be investigated in ex-situ methods. Consequently, these methods allow only a limited possibility to detect quality deviations, and if so, only with a delay. Furthermore, numerical models can only be validated insufficiently, as classic investigation methods cannot accurately determine the clinch point geometry including elastic deformations.

Computed tomography is an imaging structural analysis method that is suitable for homogeneous materials such as aluminium as well as heterogeneous materials such as concrete or composite materials. CT is used for damage analyses, for example, on drilled holes [4] or joints with semi-tubular self-piercing rivet-joints between aluminium and fibre-reinforced plastics [5]. Normally, CT is implemented as an ex-situ method. Füßel et al. also demonstrate the possibilities of CT as an in-situ method in the analysis of bonded and riveted lap joints made of fibre-reinforced plastics and aluminium [6]. The hybrid joint was loaded until failure in a shear test. By application of CT, the time sequence of the different failure phenomena could be observed. In addition, the deformation and damage of metal inserts in fibre-reinforced plastics could be tracked by in-situ CT analyses [7].

The transient dynamic analysis TDA detects changes in a structure to be analysed by means of changes in its dynamic properties. A change in the structure, such as a crack, causes a change in the frequency-dependent conductivity of the material or structure to mechanical waves. Evaluation variables used in the literature are the changing mechanical impedance [8], the dissipated energy [9] or the changed amplitude [10]. To perform TDA, mechanical waves are introduced into the structure and recorded. Both are often realised by means of applied piezoelectric actuators and sensors. For damaged fibre-plastic composites, Holeczek et al. show that the dissipated energy contributions from the damage can be clearly distinguished from the material-intrinsic dissipation of the polymer when measured by TDA due to their characteristics via frequency and amplitude [11]. With regard to joints, the method is already used to bolted joints in some publications. Esteban and Rogers investigate energy dissipation in bolted joints at high stimulation frequencies to evaluate the sensory range of piezoelectric elements [8]. Bournine et al. are working on maximising damping at the bolted joint while preserving the load-carrying capacity of a steel beam structure [10]. Wang et al. used energy dissipation to inspect bolted joints for residual torque [9]. Other approaches exist to increase the performance of energy dissipation analysis for small defects by superimposing low and high frequency stimulation of the structure [12]. With regard to clinching, Köhler et al. have already succeeded in determining differences in amplitudes during TDA testing clinch specimens with different bottom thicknesses [13]. Compared to CT, it is still more difficult to detect specific defects with TDA. With TDA, however, a significantly higher temporal resolution can be realised.

The two non-destructive testing methods thus complement each other well. The TDA quickly finds fundamental deviations in the process and the exact diagnosis is then made on the basis of the CT scan. Thus these methods can be used to detect quality deviations during clinch processes faster and in more detail. Furthermore, the results can enhance the validation of numerical models. In this paper, the development of a novel in-situ characterization method is described and a first proof-of-concept is demonstrated at the first specimen.

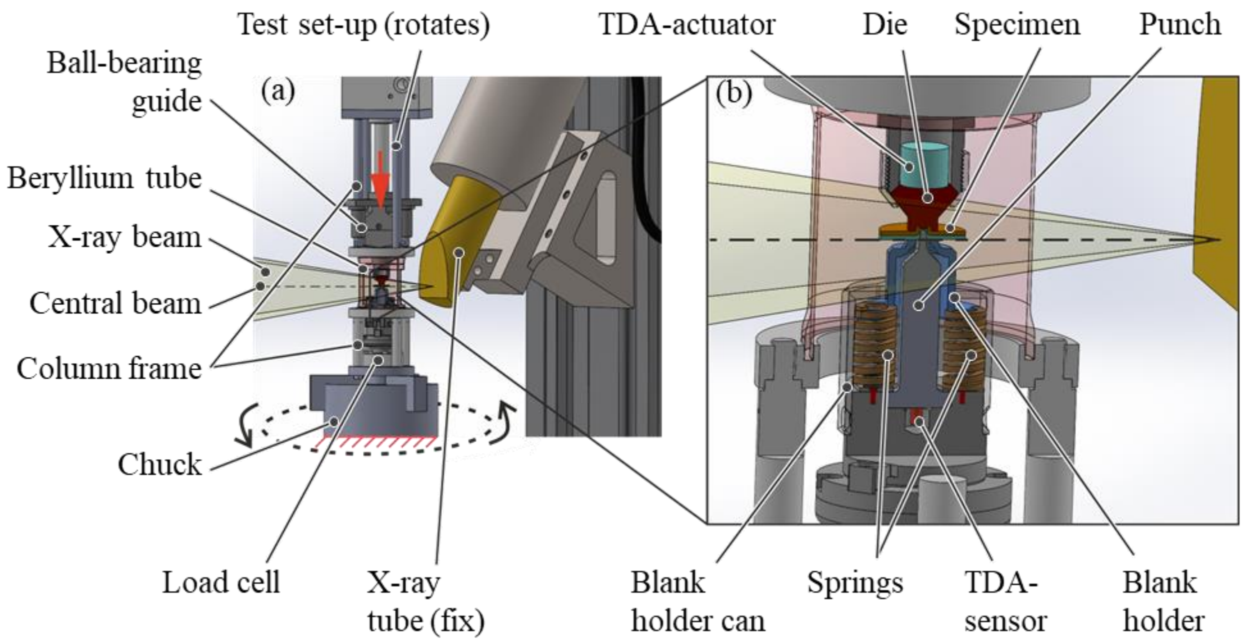

Fig. 1: In-situ test set-up in the CT-system (detector not displayed) (a) and close-up view (b) with the test specimens and the piezo actuators / -sensors for TDA fitted onto the clinching tools

Materials and Methods

In-situ CT-Clinching Setup. For the CT scans the CT-system V|TOME|X L450 from GE Sensing & Inspection Technologies GmbH (300 kV microfocus X-ray tube with flat detector) is used. Here, the tube and the detector are fix and the object being scanned rotates (cf. figure 1). The test set-up under investigation is clamped in a chuck. It consists of a column frame with ball-bearing guided adapters and a beryllium tube allowing a constant and low X-ray absorption by the frame. Furthermore, a screw jack system HSG-4-SVA-300-L-GG-AB-KGS32x5 with ball screw, worm gear and a transmission ratio of 28:1 with a rotary wheel for manual operation is mounted on top of the frame moving the adapters and the die. At the bottom of the frame, there is a load cell series K (nominal force 50 kN, nominal value 2 mV/V) from GTM Testing and Metrology GmbH. Additionally, the measurement amplifier 9243 from burster präzisionsmesstechnik gmbh & co kg is used. The signal is then recorded using a measuring card (frequency 50 Hz). This allows a force controlled manual operation of the clinching process.

In-situ CT tools and specimen. In the adapters, a clamping mandrel is used for a quick exchange of the tools. The tools consist of a blank holder, a die and the punch. The spring loaded blank holder is pushed against the sheets during punch movement preventing buckling. The springs have a total stiffness of 465 N/mm and a preload force of 785 N. The blank holder is made of high strength titanium. The punch and the die are made of silicon nitride (Si3N4) from FCT Ingenieurkeramik GmbH. These materials were identified as a suitable tool materials for in-situ CT-investigation in previous numerical [14] and experimental [15] studies. Since it is common in automotive industry [16], two 2 mm thick aluminium sheets made of Al EN AW 6014 are clinched (specimen diameter 40 mm). Since the aluminium sheets are pressed so tightly in the clinch point, the sheet interface is hardly visible in CT-scans [15]. Therefore, a 10 µm thick tin foil (diameter 12 mm) is placed between the aluminium sheets which proved to be suitable to enhance the visibility of the interface in the CT-scan [15]. Furthermore, a lubricant with a molybdenum content is applied to the surfaces in contact of the tools and to the outer surfaces of the aluminium specimens in order to enhance the detachment of the specimen after clinching.

TDA-Setup. For the TDA, defined sound waves must be introduced into the process area. For this purpose, a disc made of a piezoelectric material (PI Ceramic GmbH - type designation PRYY + 0588) is adhesively bonded to the back of the die using the epoxy resin adhesive UHU plus endfest 300 (hardener 50 %/binder 50 %). A disc of piezoelectric material (company PI Ceramic GmbH - type designation 000034947) was also adhesively bonded to the back of the die as a TDA sensor, see figure 1. To intensify the sound input of the TDA actuator and sound pick-up of the TDA sensor, seismic masses are adhesively bonded to the back of the respective piezoelectric discs. For the TDA actuator the seismic mass is 37 g and for the TDA sensor 2.3 g. In order to convert the electrical charge generated in the TDA sensor into an electrical voltage signal of practicable size, a charge amplifier type 5018 from Kistler Instrumente GmbH is used (capacity 40 pC). In order to attenuate the interfering influences of the surrounding electrical equipment, the signal of the TDA sensor is filtered by a 1st order analogue high-pass filter with a cut-off frequency of 147 Hz before entering the charge amplifier. The signals from the TDA sensor and the load cell are digitised using a National Instruments NI6356 DAQ card. The TDA actuator is excited with the help of an analogue output of the NI6356.

TDA and CT procedure. The specimen is X-ray scanned at five measuring points (MP). First when the punch is at the neutral position, second when the sheets is pushed into the cavity of the die but before it hits the anvil, third when the sheet material is drawn radially along the anvil, fourth when the sheet material fills the radial groove and finally when the targeted bottom thickness of 0.7 mm is reached. For proof of concept, no complete CT-scans are performed. Instead, the resulting clinch point geometry is quickly assessed by 2D X-ray scans.

Table 1: CT-parameter of the CT-system V|TOME|X L450 from GE Sensing & Inspection Technologies GmbH

Parameter	Unit	Value
Acceleration voltage	[kV]	250
Tube current	[µA]	150
X-ray projections		1440 (4 per 1°)
Exposure time	[ms]	1000
Voxel size	[µm]	12
Magnification		16.5

Before each X-ray scan a TDA investigation is done. The TDA measurement covers all five stages and additionally one more measuring point when the punch hits the sheets at the first time. The TDA procedure is performed in frequency steps. A program was written for this in Labview. The first stage is at an stimulation frequency of 50 Hz. This means that an electrical square-wave AC signal is applied to the TDA actuator at a stimulation frequency of 50 Hz. The amplitude of the alternating signal was set to the maximum output signal of the NI6356 equal to 10 V for all frequency stages. The stimulation is carried out for a total of 2 s. Tests have shown that at all frequencies used, a time of one second is sufficient to reach the steady state. In the time between 1.5 s and 2.0 s, the signal of the TDA sensor and the load cell is sampled at a sampling rate which always corresponds to eight times the respective stimulation frequency. The process is then repeated with a stimulation frequency of 100 Hz, 150 Hz, ..., 20000 Hz. A frequency spectrum is created from the time domain signal at the respective stimulation frequency by means of a Fast Fourier Transform using a Matlab routine. Only the amplitude at the respective stimulation frequency is taken from this frequency spectrum. An individual spectrum is created for each TDA measuring point from the stimulation frequencies and the corresponding amplitudes.

Results

In the CT-scans (figure 2 a-e), it can be seen that a general good image quality is achieved. Nevertheless, there are some streak artefacts going away from the edges parallel to the central beam. The clinching process can be clearly identified, which runs symmetrically until the failure of the die. The failure of the die can be identified during the CT-scan when the ring groove is filled. Notably, the crack starts at the bottom of the groove and goes 360°. The grey contour in the space between the sheet surface and the die, highlighted in the red ring of MP 3, is the lubricant.

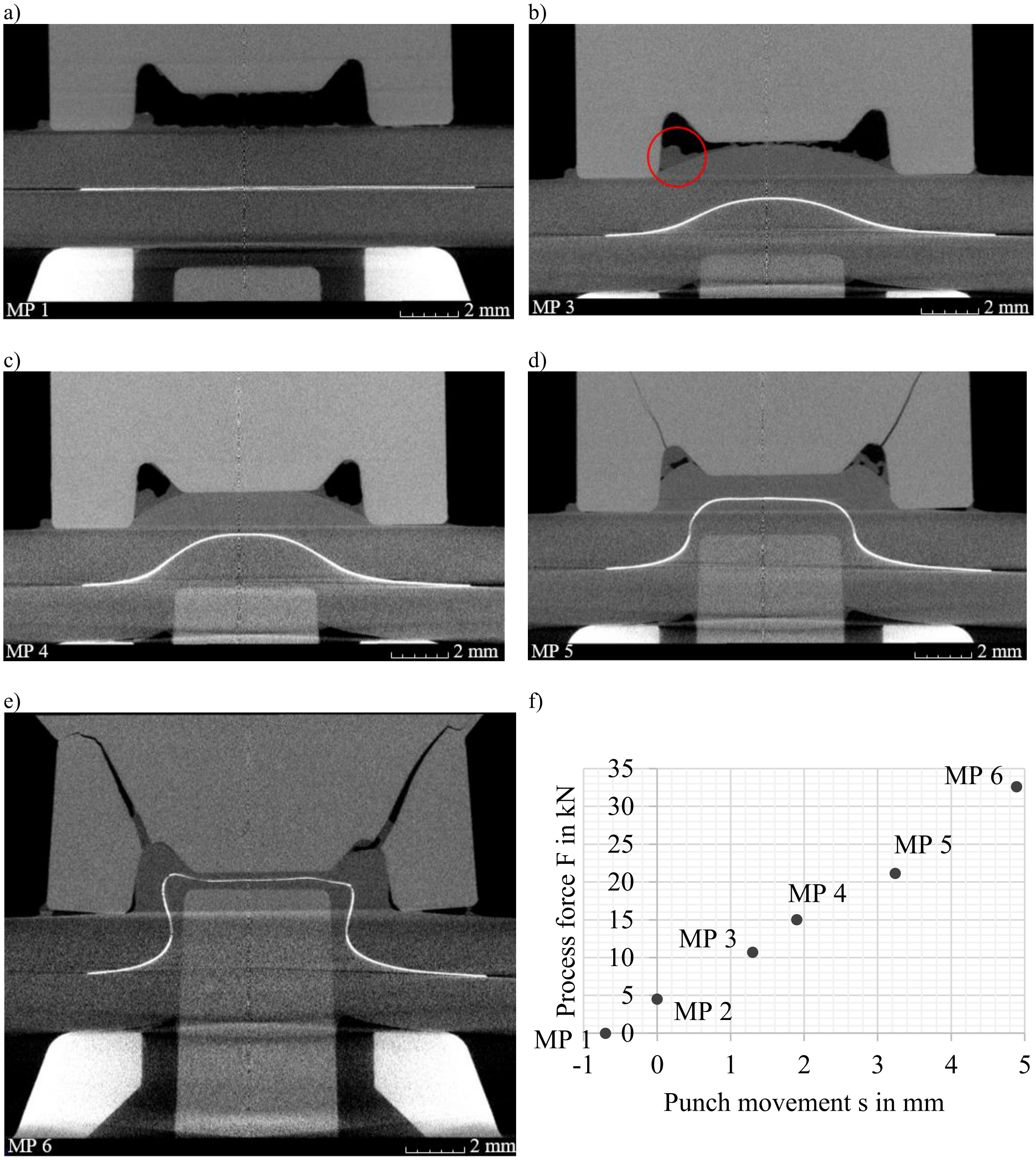

Fig. 2: CT images of the in-situ clinching process (a-e)and process force and punch movement during the clinching process (f)

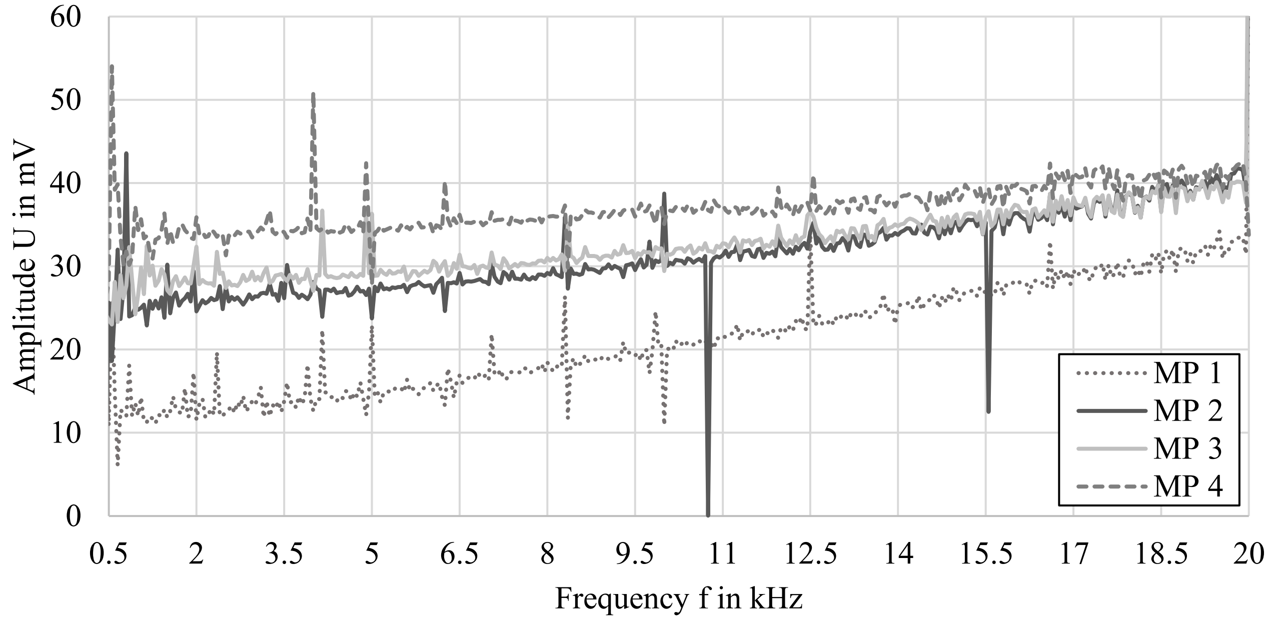

Fig. 3: Frequency spectra of the TDA measuring points 1 to 4

Basically, the spectra of the TDA in figure 3 are very similar. All graphs increase with frequency and show peaks at the same frequencies. Especially in the frequency range above 11 kHz, the individual spectra show an almost congruent course. However, the increase of the spectra is differently pronounced, so that the amplitudes of MP 1 in the low frequency range are about 20 mV lower than the amplitudes of MP 4. In the higher frequency range, the two spectra are only separated by about 10 mV. The most obvious difference between the spectra of the different measuring points is the increasing amplitude height over the entire frequency bandwidth. This development can be explained by the increased mechanical coupling of the stimulated die to the punch with its TDA sensor on the rear from MP 1 to MP 4. The improved mechanical coupling between MP 1 to MP 4 is reflected in the increasing punch force, see figure 2 f, and in the increasing contact area between punch, clinch plates and die, see figure 2 a-c.

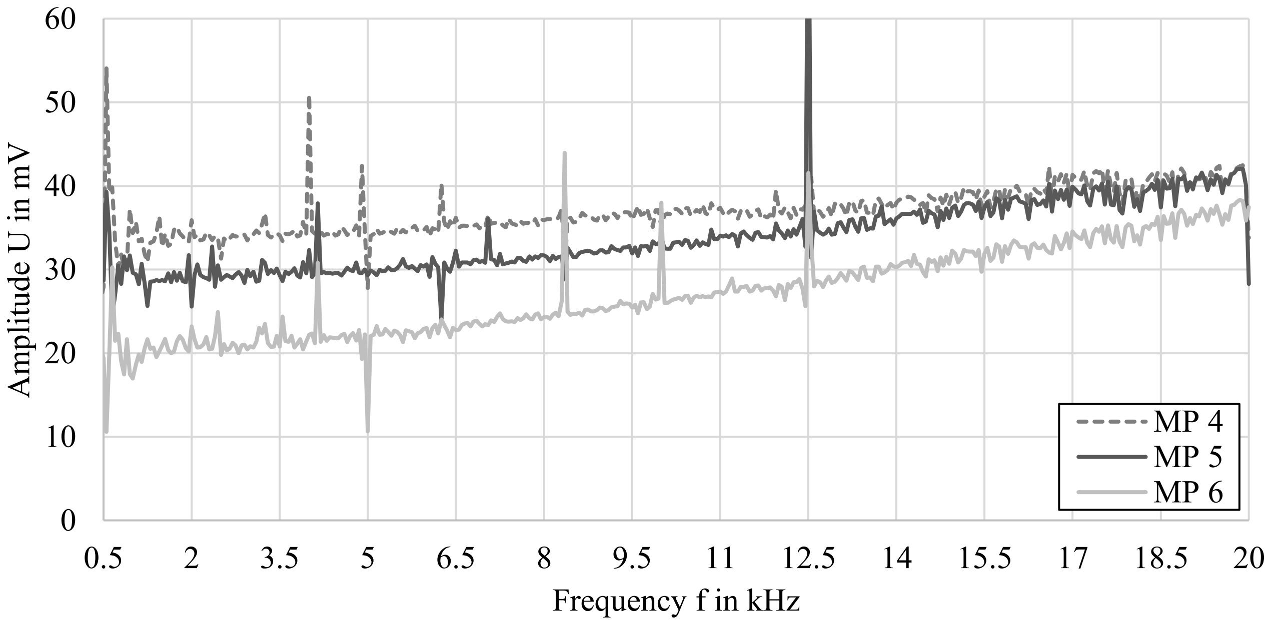

Fig. 4: Frequency spectra of the TDA measuring points 4 to 6

In contrast to MP 1 to MP 4 in figure 3, the amplitude height decreases in figure 4 between MP 4 and MP 6, although the applied punch force continues to increase. The reason for this is probably the progressive crack in the die, which reduces the mechanical coupling via the outer ring of the die.

In addition to the signal from the TDA sensor, the signal from the piezoelectric load cell was also processed in the same way during the TDA. In the following figure, the TDA result of MP 3 is plotted for a comparison of the signals for both sensors:

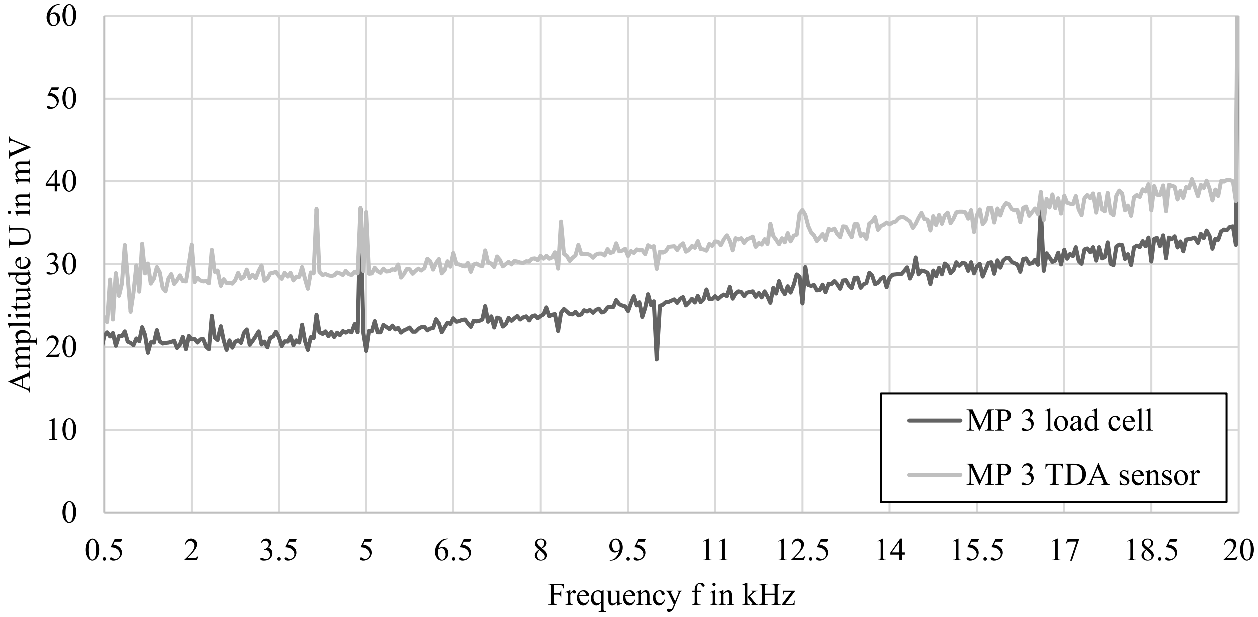

Fig. 5: Frequency spectra of the TDA measuring point 3 from load cell signal and TDA sensor signal

Figure 5 shows that the signal from the load cell is 8-10 mV smaller over the entire frequency range, but otherwise shows almost the same curve as the TDA sensor. The smaller amplitudes could be explained by the greater distance from the signal source and the associated stronger damping of the mechanical wave on the way to the load cell.

Summary and Conclusions

To the author's knowledge there have been no reports about testing the clinching process in in-situ CT. This approach, however, can increase the knowledge about deformation and damage phenomena occurring during this process. As a consequence the clinching process can be improved and numerical models can be validated more accurately. Additionally, using the TDA system to control a clinching process, process deviations can be detected faster. In this paper, an apparatus for investigating a clinching process of metal sheets using in-situ CT and TDA is described.

Tool materials that are otherwise difficult to radiate with X-rays are replaced by a die and a punch made of the ceramic material Si3N4. This allows it to image a complete clinching process in five CT scans. However, the die breaks during the test. This fracture correlates with numerical analyses in [14]. Despite the partial destruction of the die, the clinching process can be continued up to a target bottom thickness of about 0.7 mm. The experiment thus only partially proves the feasibility of in-situ CT of clinching processes. In all CT images, the thin tin layer between the aluminium sheets makes the interface clearly visible. However, the influence of the tin layer on the formation of the clinching point must be cleared in future works. In the CT scans, some streak artefacts are visible starting from the edges parallel to the centre beam (cf. figure 1). These irregularities could be corrected in further investigations by adjusting the angle of the in-situ clinching device. The lubricant containing molybdenum is visible on the CT images, too. Since it exhibits a similar grey value as the aluminium of the specimen, the recognisability of the sheet is reduced. To avoid this effect, a lubricant that does not contain molybdenum should be used in further CT examinations. In order to prevent further die breakage in future investigations, a titanium alloy will be used as die material.. With an in-situ clinching process without tool failure, the shape of the resulting clinched specimen will be compared with a specimen made with a conventional clinching tool. Thus the influence of the tool materials, the tin layer and the lubricant can be figured out. Moreover, the reproducibility of the in-situ method can be investigated. Thereby the validity and significance of the findings can be examined.

To complement the CT analysis, which is in principle slow and reliant on process interruptions, the method of transient dynamic analysis is being tested in the same experimental setup. Changes in the dynamic behaviour in the clinch process zone are tracked by actively introducing and recording sound waves. The author promotes that this method has the potential to run concurrently with the process and to quickly detect inadmissible changes. For TDA, piezoelectric elements are applied to the die and punch as actuator and sensor. In the experiment described here, TDA is carried out during six process interruptions in order to monitor differences in the dynamic behaviour of the process zone during clinching in a low-noise environment.

There are clear differences between the individual TDA results at different points in time during the clinching process. Until the crack in the die is visible in the CT, the TDA results of the advancing clinching process can be distinguished by a basically identical frequency response but steadily increasing amplitudes. With increasing crack length in the die, clearly reduced amplitudes become visible in the TDA results. The differences in the TDA results during the test confirm the assumption that process tracking of the clinching process as well as the detection of unexpected defect cases could be possible by means of TDA.

The TDA is carried out on the basis of a specially installed sensor as well as on the basis of the signal from a load cell integrated in the experimental setup. The comparison between the two sensors show qualitatively equal TDA results for both sensors. Although the amplitudes of the load cell signal are somewhat smaller than those of the TDA sensor, the suitability of the load cell as a TDA sensor can still be determined. For further investigations, the TDA sensor could be substituted by using the load cell alone.

In all TDA results, a seemingly linear increase of the amplitudes with increasing frequency is recognisable in the measurement data of the TDA sensor as well as in the load cell. The author assumes that this effect is caused either by the dynamic behaviour of the experimental setup or by the resonance behaviour of the TDA actuator. In further investigations, these effects will be examined in a wider frequency range.

Finally, the following main conclusions can be drawn from the investigation:

- A die and punch made of Si3N4 allow a CT scan of a complete clinching process in high quality. However, the die breaks during the test.
- The tracking of the clinching process can be achieved by TDA.
- The Detection of unexpected defect cases could be possible by means of TDA.

Acknowledgements

This research was funded by the German Research Foundation (DFG) within the project Transregional Collaborative Research Centre 285 (TRR 285) (project number 418701707), sub-project C04 (project number 426959879).

References

[1] Deutscher Verband für Schweißen und verwandte Verfahren e. V., Mechanisches Fügen, DVS Merkblätter und Richtlinien; 10. Düsseldorf: DVS-Verlag, (2009).

[2] J. Varis, Economics of clinched joint compared to riveted joint and example of applying calculations to a volume product, J. Mater. Process. Technol. 172 (2006) 130-138.

[3] Y. Tan, O. Hahn, and F. Du, Process monitoring method with window technique for clinch joining, ISIJ Int. 45 (2005) 723-729.

[4] L. Pejryd, T. Beno, and S. Carmignato, Computed tomography as a tool for examining surface integrity in drilled holes in CFRP composites, Procedia CIRP 13 (2014) 43-48.

[5] W. G. Drossel, R. Mauermann, R. Grützner, and D. Mattheß, Numerical and experimental analysis of self piercing riveting process with carbon fiber-reinforced plastic and aluminium sheets, Key Eng. Mater. 554–557 (2013) 1045-1054.

[6] R. Füßel, M. Gude, and A. Mertel, In-situ x-ray computed tomography analysis of adhesively bonded riveted lap joints, in: 17th European Conference on Composite Materials. Munich, 2016.

[7] F. Pottmeyer, J. Bittner, P. Pinter, and K. A. Weidenmann, In-Situ CT Damage Analysis of Metal Inserts Embedded in Carbon Fiber-Reinforced Plastics, Exp. Mech. 57 (2017) 1411-1422, 2017.

[8] J. Esteban and C. A. Rogers, Energy dissipation through joints: Theory and experiments, Comput. Struct. 75 (2000) 347-359.

[9] F. Wang, L. Huo, and G. Song, A piezoelectric active sensing method for quantitative monitoring of bolt loosening using energy dissipation caused by tangential damping based on the fractal contact theory, Smart Mater. Struct. 27 (2017 0-17.

[10] H. Bournine, D. J. Wagg, and S. Neild, Vibration damping in bolted friction beam-columns, Proc. ASME Des. Eng. Tech. Conf. 330 (2009) 365-372, 2009.

[11] K. Holeczek, P. Kostka, and N. Modler, Dry friction contribution to damage-caused increase of damping in fiber-reinforced polymer-based composites, Adv. Eng. Mater. 16 (2014) 1284-1292.

[12] Z. Zhang, M. Liu, Z. Su, and Y. Xiao, Quantitative evaluation of residual torque of a loose bolt based on wave energy dissipation and vibro-acoustic modulation: A comparative study, J. Sound Vib. 383 (2016) 156-170.

[13] D. Köhler, B. Sadeghian, R. Kupfer, J. Troschitz, M. Gude, and A. Brosius, A Method for Characterization of Geometric Deviations in Clinch Points with Computed Tomography and Transient Dynamic Analysis, Key Eng. Mater. 883 (2021) 89-96.

[14] D. Köhler, R. Kupfer, and M. Gude, Clinching in in-situ CT—A numerical study on suitable tool materials, J. Adv. Join. Process. 2. (2020).

[15] D. Köhler, R. Kupfer, J. Troschitz, and M. Gude, Clinching in In-situ CT – Experimental Study on Suitable Tool Materials, in: ESAFORM 2021, 24th International Conference on Material Forming, Liège, 2021, pp. 1–11.

[16] R. Bhattacharya, M. Stanton, I. Dargue, G. Williams, and R. Aylmore, Forming limit studies on different thickness aluminium 6XXX series alloys used in automotive applications, Int. J. Mater. Form. 3 (2010) 267-270.