NON-DESTRUCTIVE ULTRASONIC WALL THICKNESS MEASUREMENT OF MINERAL HOLLOW BODIES

ZERSTÖRUNGSFREIE ULTRASCHALLECHOWANDSTÄRKENMESSUNG MINERALISCHER HOHLKÖRPER

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SUMMARY

Functionally Graded Concrete (FGC) is a way of reducing concrete usage through targeted placement of mineral hollow bodies inside the building component. These mineral hollow bodies, produced by rotational moulding, may have defects that are not detectable from the outside. Therefore, a non-destructive testing method is proposed in this contribution. The ultrasonic echo method was adapted and validated for targeted wall thickness measurement. The proposed quality assurance aims to detect critical material distribution patterns inside the mineral hollow body. By identifying faulty mineral hollow bodies, higher processing quality and lower production efforts can be achieved for upscaled production.

ZUSAMMENFASSUNG

Gradientenbeton strebt eine Gewichtsreduzierung durch gezieltes Einbringen von Hohlkörpern im Bauteilinneren an. Diese mineralischen Hohlkörper, welche per Rotationsgussverfahren hergestellt werden, können äußerlich nicht sichtbare Mängel aufweisen. In diesem Beitrag wird daher eine zerstörungsfreie Prüfmethode vorgestellt. Hierfür wurde die Ultraschall-Echomethode zur Wanddickenmessung angepasst und validiert. Die vorgeschlagene Qualitätssicherung trägt dazu bei, kritische Materialverteilungen an der Hohlkörperinnenseite zerstörungsfrei zu erfassen. Durch Identifikation der mangelhaften mineralischen Hohlkörper können eine höhere Produktionsqualität und niedrigere Herstellungsaufwände erreicht werden.

1. INTRODUCTION

To address construction-related environmental issues, new approaches have to be found [1, 2]. Concrete, being the most produced material by humankind, is crucial for achieving this goal [3]. That is why the ILEK, together with several partners, is focusing its research on lightweight and sustainable concrete solutions [4-6]. Among these, Functionally Graded Concrete (FGC) follows the idea of purposeful placement of mineral hollow bodies inside a building component according to the prevailing stress distribution and utilization [7]. This allows for significant mass reduction in FGC components and enables sorted material recycling, omitting plastic void formers. The tailored placement of mineral hollow bodies in FGC is determined by methods of previous investigations [8].

Mineral hollow bodies with different geometries and dimensions (Fig. 1, left) have already been successfully produced by rotational moulding in an experimental research environment. For this, a liquified and curing-accelerated mortar suspension is poured into a two-part mould which is subsequently put into a biaxial centrifuge (Fig. 1, right) [8].

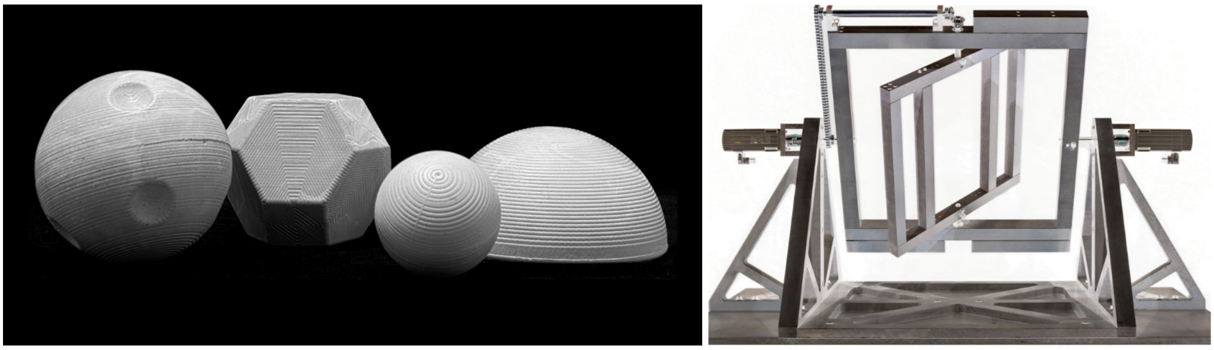

Fig. 1: Different mineral hollow body geometries (left) and prototypical biaxial centrifuge for their production (right) [8]

However, past production cycles showed distinct material distributions that compromised quality. Mineral hollow spheres without external defects (holes and breaches) can still show critical thickness variation patterns (Fig. 2). They are not externally visible, and thus need to be identified by destructive or by non-destructive methods.

In order to unlock the potential of FGC in tomorrow's construction industry, the production of mineral hollow bodies must be scaled up [9]. Fast and reliable quality control measures in large-scale manufacturing ensures the economical production and structural integrity of the mineral hollow bodies during transportation to the construction site and casting of the FGC component. This contribution presents a method for evaluating the quality of material distribution without opening and thereby excluding the probed mineral hollow bodies from production.

A non-destructive testing method is needed to ensure production quality while minimizing the scrap rate of mineral hollow bodies. For this purpose, the ultrasonic echo method for wall thickness measurement is proposed.

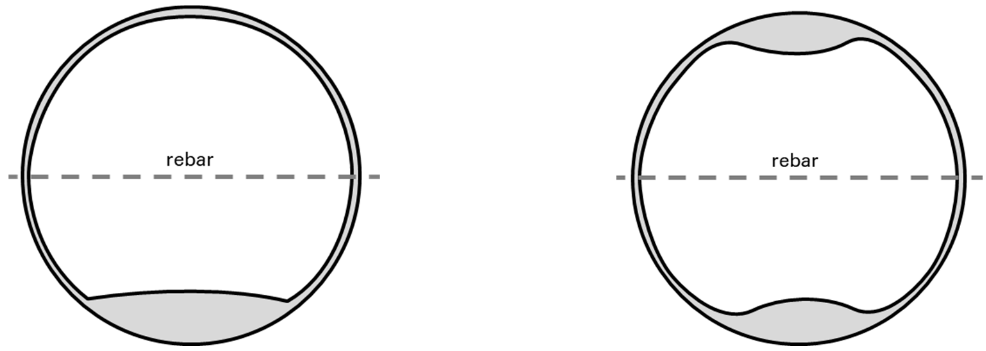

Fig. 2: Cross-sectional view of two critical material distribution patterns: sinking to bottom after rotational moulding process (left) and ring-shaped accumulation (right)

2. VALIDATION OF THE PROPOSED TESTING METHOD

The ultrasonic echo method is widely used for measuring wall thicknesses of all kinds of homogenous and isotropic materials. For structural purposes, it is mainly used for non-destructive testing of steel and concrete. Concrete elements are tested in sounding ranges of several centimetres up to a few meters [10, 11]. Filigree mineral hollow bodies with 1-4 mm wall thicknesses fall below these common applications.

A *Waygate Technologies Krautkramer USN60* ultrasound device (Fig. 3, left) was used together with two different transducer types, which subsequently were compared: Firstly, a dual-element transducer (*Krautkramer SEB4KF8*), comprising separate transducers which function independently as transmitter and receiver of ultrasonic signals. These transducers are commonly used for wall thickness and flaw measurement of corroded and rugged surfaces [10]. The transducer used in the experiment had a nominal frequency of 4 MHz, a diameter of 8 mm, and a focal distance of 6 mm [12]. Secondly, the single-element transducer (*Krautkramer MB2F*) consists of a single transducer that simultaneously transmits and receives ultrasonic signals. The transducer used in this experiment has a nominal frequency of 2 MHz, a diameter of 10 mm, and a near-field length of 8 mm.

Due to this design, it can measure higher thicknesses with enhanced accuracy [12].

To evaluate the validity of using the ultrasonic echo method in this application, several mineral hollow bodies were investigated. Each one was measured indirectly via the ultrasonic echo method with both transducers and directly via a dial gauge (Fig. 3, middle). Measuring points were distributed in 15° intervals along axes A and B (Fig. 3, right). All points were measured 10 times . Afterwards, the mineral hollow bodies were cut open and measured again directly by dial gauge.

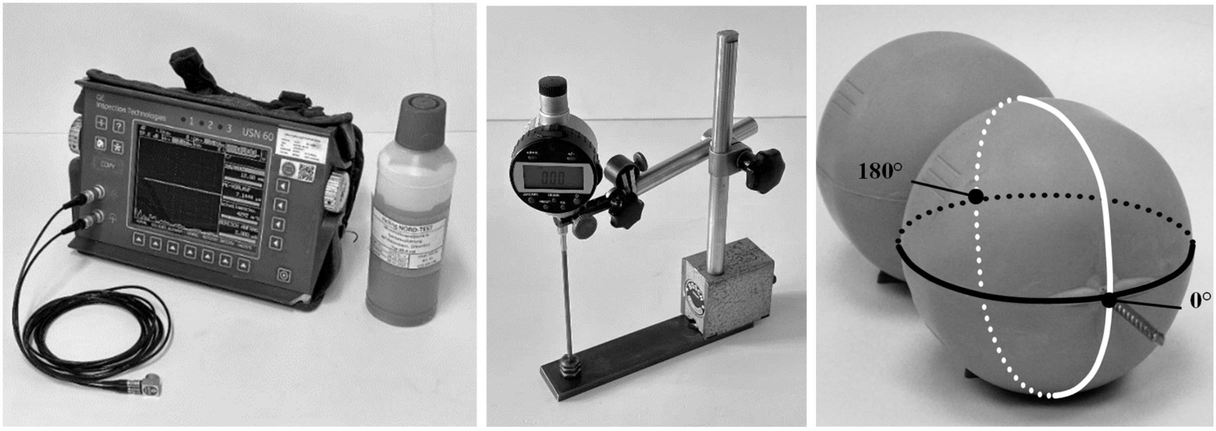

Fig. 3: Ultrasonic testing device (left), dial gauge (middle) and respective measuring axes A (black) and B (white) (right)

3. MEASUREMENTS AND FINDINGS

In the following, a summary of the experimental results obtained from the measurement of 16 specimens is presented. This is intended to illustrate the accuracy of the two different ultrasonic transducers and finally introduce a method to accurately predict the location of imperfections.

3.1 Utilisation of the Dual-Element Transducer

The indirect measurement of mineral hollow body no. 22.02.-2 with the dual-element transducer is compared to the directly measured thickness in the A axis (Fig. 4). It can be observed, that the obtained ultrasound values show a close match to the directly measured values. Only a few measuring points reveal small deviations. In this case the ultrasonic method is representative regarding the true value of wall thickness.

On other specimen with clumps or material accumulations (artifacts) on the inside, this level of accuracy could not be obtained. Fig. 5 displays the obtained wall thickness measurement of the mineral hollow body no. 22.02-3 with an artifact covered inside near the annular measuring region of axis A (cf. Fig. 5, top right). A significant deviation between direct and indirect measurement can be observed, but only for the specific regions near the artifacts (cf. Fig. 5, left).

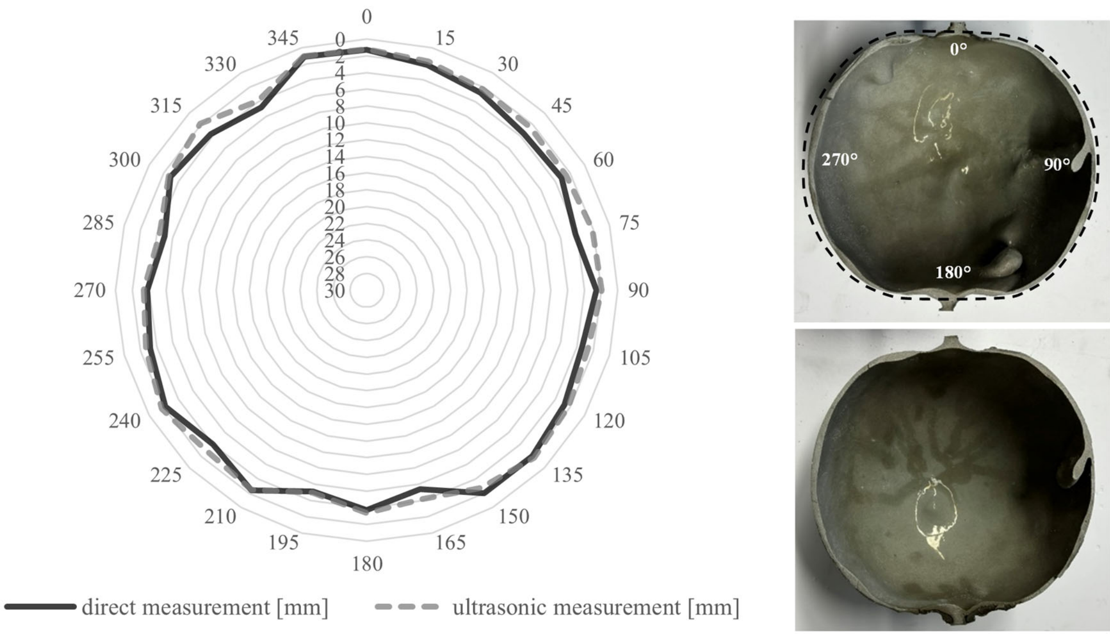

Fig. 4: Obtained measurements and radial visualization scaled by 2.5 (left), cut-open view (right) of the mineral hollow body no. 22.02.-2 in the same plane (axis A)

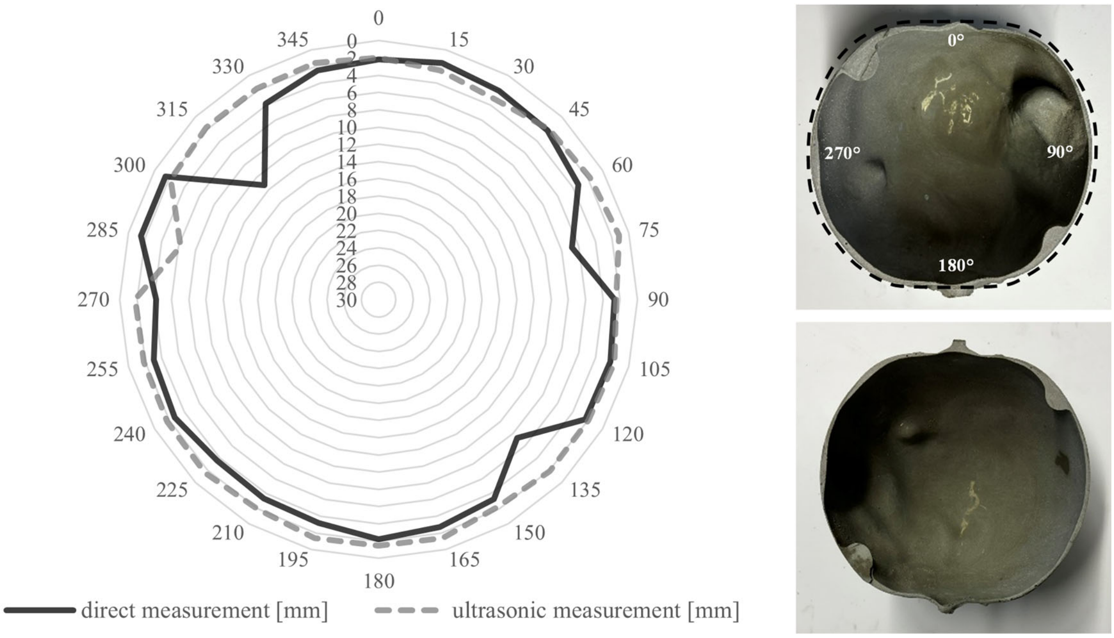

Fig. 5: Obtained measurements and radial visualization scaled by 2.5 (left), cut-open view (right) of the mineral hollow body no. 22.02-3 in the same plane (axis A)

A quality deviation could be observed with mineral hollow body no. 28.02-3, displayed in Fig. 6. Here a large accumulation of concrete around one point can be observed in the B axis. This pattern of material accumulation matches the depiction of critical distribution patterns as shown in Fig. 2, left. The ultrasonic measurement results could not display this kind of accumulation correctly. Whether the wall thickness exceeding the focal range of the transducer or the non-parallelism of the outer and inner surfaces impaired the measurement remains unclear.

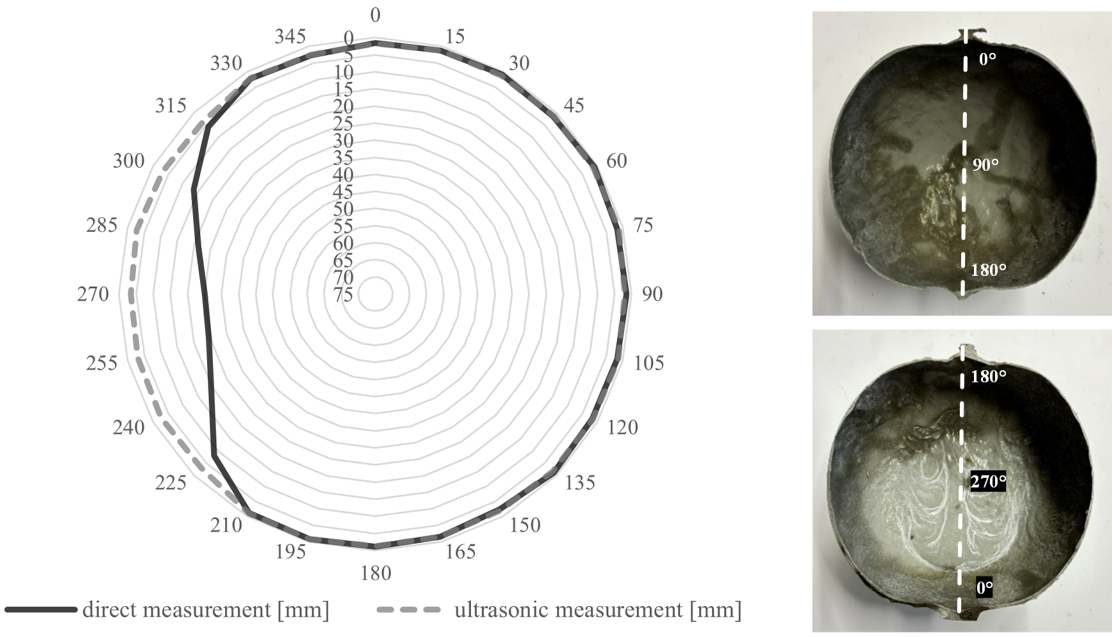

Fig. 6: Obtained measurements and radial unscaled visualization (left), cut-open view (right) of the mineral hollow body no. 28.02-3 in the orthogonal plane (axis B)

3.2 Utilisation of the Single-Element Transducer

A single-element transducer was used to measure areas with a much higher wall thickness, in which the dual-element transducer failed. Again, the before-mentioned mineral hollow body no. 28.02-3 was examined. In addition to the dual-element transducer, the single-element transducer was used to compare the results in Fig. 7. Because of the near field length, an interpretable signal was only produced on the thicker areas of the shell. But even in this restricted area, only one measurement at 270°could depict the actual thickness correctly.

A strong correlation between the parallelism of inside and outside surfaces and the accuracy of the ultrasonic measurement can be observed. Measuring points in which the inside surface is not parallel to the outside surface could not be displayed adequately by the single-element transducer. Therefore, a non-destructive measurement with this single-element transducer is not trustworthy without any knowledge about the orientation of the inside surface.

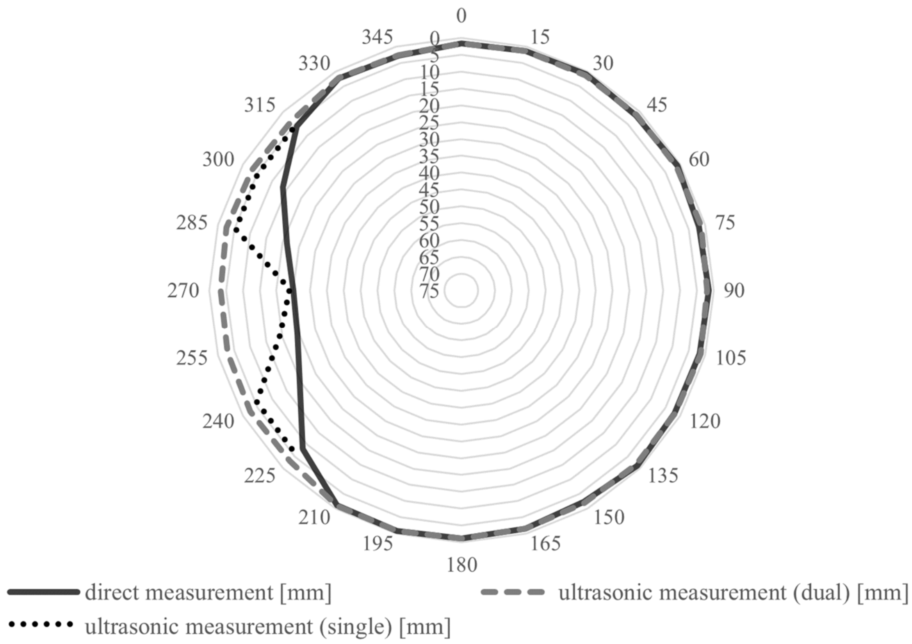

Fig. 7: Resulting measurements of dual-and single-element transducers in radial unscaled visualizations of the mineral hollow body no. 28.02-3 in the orthogonal plane (axis B)

3.3 Localization of Accumulations Through Standard Deviation

Both transducers could not reliably determine the directly measured wall thickness at every point. However, the dual-element transducer presented a higher reliability than the single-element one. Still, the accuracy of ultrasonic measurement cannot be verified without knowledge of the inside surface. Under the given premise of a non-destructive testing method, a statistical approach is presented, implementing another way to localise material accumulations with the dual-element transducer. It is carried out on the mineral hollow body no. 28.02-3 in the B axis (cf. Fig. 7) and displayed in Table 1.

By observing the standard deviation of repetitive measurements in each measuring point, a strong correlation between the high scattering of single values and a high deviation between direct and indirect measurement can be drawn: A high standard deviation spreading over multiple measuring points indicates a probable measuring fault and furthermore a high chance of material accumulation.

Table 1: Evaluation of the Dual-Element Transducer Measurements

Position [°]	Ultrasonic mean value (DEP) [mm]	Standard deviation [mm]	Direct measurement [mm]	Difference ultrasonic-direct [mm]
0	1.7	0.2	1.6	0.1
15	1.4	0.1	1.3	0.1
30	1.2	0.1	0.8	0.4
45	1.2	0.2	1.5	-0.3
60	1.3	0.2	0.9	0.4
75	1.2	0.2	1.8	-0.6
90	2.0	0.2	1.5	0.5
105	1.3	0.1	1.7	-0.4
120	1.6	0.4	1.8	-0.2
135	1.6	0.5	1.1	0.5
150	1.9	0.0	2.3	-0.4
165	1.5	0.3	1.5	0.0
180	1.2	0.1	1.1	0.1
195	0.9	0.1	0.8	0.1
210	1.0	0.1	1.0	0.0
225	3.0	1.2	8.2	-5.3
240	2.6	1.3	19.5	-16.9
255	3.0	1.1	24.5	-21.5
270	3.5	1.2	25.0	-21.5
285	2.7	0.8	21.3	-18.6
300	3.2	0.5	13.7	-10.5
315	3.7	1.5	5.9	-2.2
330	2.1	0.3	2.2	-0.1
345	2.6	0.3	2.7	-0.1
mean	**2.0**		**6.0**	

This observation can be explained by several factors which apply to points with anomalies. A non-parallel reflective surface or a wall thickness that is too high for the used transducer causes an inconclusive echo pattern that cannot be interpreted correctly. Therefore, a high scattering of the individual measurements of one point on the sphere shell is obtained. This example shows clearly that the ultrasonic echo method is capable of localising material accumulations inside the mineral hollow body. It is achieved not by measuring a sufficiently accurate absolute value once but by evaluation of scatter patterns in the generated data set.

To put this method to test, other hollow bodies of past production cycles were measured in the same way. It is known that these samples will probably exhibit a critical material distribution. Consequently, ultrasonic measurement should exhibit anomalies in the points 90° and 270° (Fig. 8). Around these ring-shaped regions, an overall higher wall thickness and scattering were measured, meaning that these areas will likely have material accumulations on the inside. Because the same pattern is depicted along both axes, a critical circular accumulation is possible. By interpreting these patterns, a critical distribution of material can be detected (c.f. Fig. 2, right).

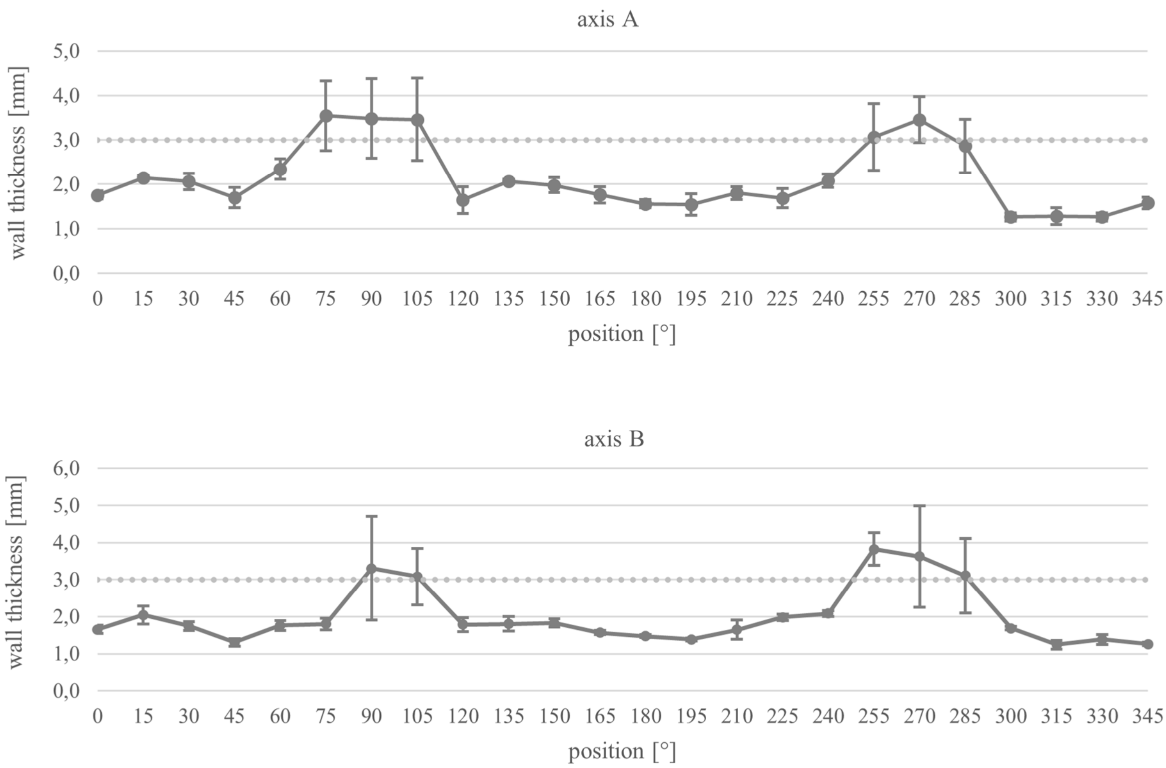

Fig. 8: Resulting ultrasonic measurements and linear visualizations of sample specimen from past production cycles

4. SUMMARY AND OUTLOOK

During production, mineral hollow bodies can develop distinct material accumulations on the inside. These are directly linked to a lower quality and thus should be identified. This contribution presented a non-destructive method for wall thickness measurement and identification of faulty hollow bodies. The suitability of the proposed ultrasonic method has been proven partially. Under certain circumstances dual-element transducers are able to generate values which are representative for the true wall thickness.

To evaluate the reliability of the values generated hereby, the standard deviation of each measuring point can be used. A high scattering indicates an unreliable measurement. If a high standard deviation can be observed across several adjacent points, a material accumulation is given. By taking these findings into account, known patterns of faulty material distribution inside the hollow bodies can be identified.

Clearly, the devices and transducers used in this study, depict only a small portion of available technology. There is a variety of non-destructive testing methods and special equipment for the application of wall thickness measurement. In the present case of a double-curved surface and a small wall thickness, a rounded and focused probe head could achieve a significant improvement of accuracy. The same potential can be expected by using phased array transducers.

Nevertheless, a basic usability of the presented method was proven and is an important step towards non-destructive quality assurance for mineral hollow bodies used in FGC. This helps to scale up the production and is essential to employ this novel technology on the construction sites of tomorrow.

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