Imaging spot weld inspection using Phased Array technology – new features and correlation to destructive testing

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This presentation focuses on the suitability of using imaging ultrasonic phased array technology (PAUT) for the inspection of resistance spot welds. In this study 2- and 3-layer joints with a single sheet thickness of 0.7 up to 3 mm are tested using PAUT as well as the destructive hammer and chisel testing with a metallographic section analysis. The results of the testing methods are correlated and tested for deviations. This analysis will especially discuss the measurement accuracy of the nugget diameter. Additionally the precision of the attenuation due to structural transformation of high-strength steel and the residual wall thickness in the welded area of aluminium PHAsis is providing optional.
The phased array inspection of the welded spots was realized with the PHAsis[one] inspection device. With 121 ultrasonic elements in an 11 x 11 matrix, a physical resolution better than 0,35mm is achieved. More than 700 measuring points are documented per spot weld as a fast electronic scan image. For the adaption of the probes to the test part, the water path is used with the reliable bubbler technique or a fixed rexolite wedge. Like the conventional spot weld inspection with only one ultrasonic element, up to 500 to 800 spots can be inspected per shift. The software supports the spot weld testing by scan plans for programmed parts or by a “free testing mode”, where the user can test various spot welds, detached from set inspection plans.
For the test plan preparation, often all spots of the specimen are manually tested in an optimized order. The “free testing mode” offers detachment and simultaneously the possibility to store all data, sequences and evaluations. By using PHAsis[manager] PC-Software, the collected data can be transferred into a new test plan for the following serial inspection. This final test plan then can be synchronized with relevant inspection devices and easily be realized by a user with much less ultrasound know-how.

1. PHAsis[one] Phased Array ultrasonic inspection device for the fast and imaging spot weld inspection

1.1 PHAsis spot weld inspection solution

PHAsis is an ultrasonic inspection solution consisting of the PHAsis[manager] administration software and [one] or more PHAsis[one] inspection devices for the precise valuation of resistance welded spots of steel- or aluminum sheets, adhesives and solder joints. It is ideally suited for the inspection of 2- and 3-layer joints with a single sheet thickness of 0.7 up to 5 mm.
PHAsis[one] is the first phased array ultrasonic inspection device offering a previously unattained physical resolution of the spot weld diameter more precise than 0.35 mm.

The device operated with 121 ultrasonic elements in an 11x11 matrix. Using the Phased Array technology more than 700 measuring points are recorded per spot weld. The inspection time is just a few seconds per spot.
PHAsis^{one} provides data on the diameter of the welding spot, the remaining wall thickness of the welded area as well as the sound attenuation caused by structural transformation as possible evaluation criteria for zinc adhesion bonding.

Figure 1. PHAsis^{one} Phased Array ulteasonic inspection device

1.2 Inspection modes

PHAsis^{one} inspection devices can be used for two different inspection tasks:

- Inspection according to a test plan (for the fast use in production)
- Free testing without a test plan (for laboratory usage, the use in prototype construction or for a sampling within the production)

Using a test plan, the user is guided step by step through the inspection by an imaging spot weld site plan. The required parameter data are already deposited in the test plan. Therefore no manual setup is needed.

The free testing enables a fast inspection of various spot welds, detached from set inspection plans. The user can either set all parameter data freely – what requires a little bit of ultrasonic inspection know how – or use deposited data sets. In this case the user just needs to select the kind of material and the material thickness. If the material thickness is not known, the single sheet thickness can easily be determined with the wall thickness measurement mode of the inspection device. Thereby the user has still access to the full functionality as known from the testing according to inspection plans.
After the inspection, the results of the free testing can be transferred into an inspection plan and a serial inspection.

1.3 Testing with PHAsis[one]

The probe is connected to the test part by means of the water path nozzles and its reliable bubble technique. The user can choose between four different water path nozzles or a fixed rexolite wedge according to present accessibility and surface quality.

The PHAsis[device] inspection and evaluation software on the device is specifically designed by VOGT Ultrasonics for quick use during production. The intuitive operation guarantees a minimum need of training. The software of the device supports the customer with a live D-Scan and runtime-based alignment indications for the optimum positioning of the probe on the spot weld to be inspected.

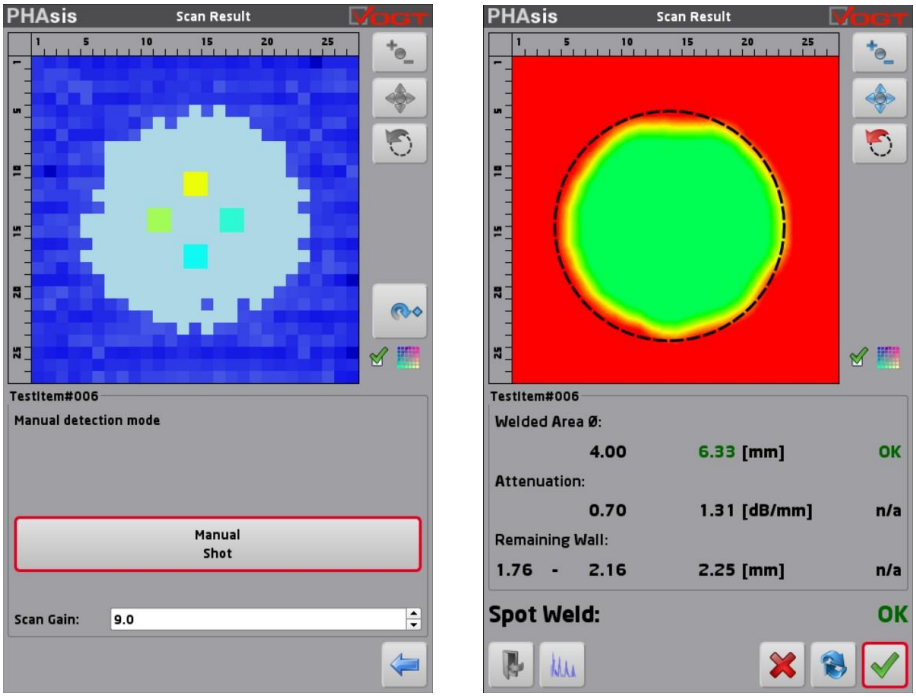


Figure 2. Left: Live-C-Scan for positioning and vertical focussing of the probe on the spot weld surface; Right: Automatically created evaluation proposal

The imaging display of the phased array technology ensures the safe evaluation of the inspection results. The created display of the spot weld with colored depth imaging of the welded areas shows defects in the welding, e.g. pores or too small welding spots.
By freezing the D-scan (depth of reflectors) the inspection system automatically provides an evaluation as a proposal.

The compact and robust housing and its low weight of 3.5 kg make PHAsis[one] the ideal equipment for mobile operation

1.4 Centralized administration of test plans and result evaluation

All data are organized by means of the PHAsis[manager] administration software and are synchronized with the PHAsis[one] ultrasonic inspection device. Default parameter data for the free testing and test plans can be created and test results evaluated.

All test plan and result data are stored in a PHAsis database. The database is accessed via the PHAsis[service] utility program. The PHAsis[manager] administration software and the PHAsis[one] inspection devices communicate with PHAsis[service] via LAN connection.
The PHAsis database can be adapted to the existing customer's database. Thus, existing test plans can be transferred to PHAsis.

2. Test results and correlation with destructive testing method

2.1 Used probes/materials

Extensive tests with 2-layer joints of steel and aluminium were performed. In the following we show the correlation between the ultrasonic inspection results and the results of the destructive testing.
The inspections results for correlation with the destructive testing were determined with the inspection of the layer joints shown in Table 1.

Table 1. Used layer joints

No.	Material	Thickness
1	Steel	0,7 mm / 0,8 mm
2	Aluminium	1,6 mm / 1,6 mm
3	Aluminium	1,0 mm / 1,0 mm
4	Aluminium	1,2 mm / 3 mm

2.2 Presentation of results for steel (2-layer joints)

The presentation of the results for layer joints of steel is based upon the inspection results according to no. 2 in Table 1. The results are based upon a 2-layer joint.
Figure 3 shows a representative result for an ultrasonic inspection with PHAsis[one] inspection device (Left) and the appropriate test result of the destructive testing (Right).

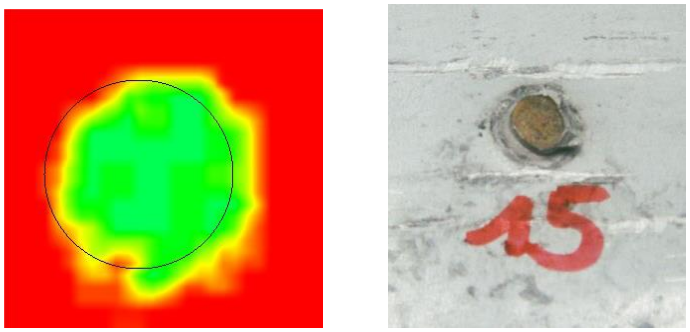


Figure 3. representative result for steel 0.7/0.8 mm (Left: ultrasonic inspection result; Right: destructive testing result)

The inspection results for this specific spot weld are as follows:
Spot weld diameter (PHAsis[one]): 5.3 mm
Spot weld diameter (destructive testing): 5.0 mm

So the deviation between the destructive testing and the ultrasonic inspection amounts 0.3 mm only. The evaluation of all inspection results approves that the correlation between the PHAsis[one] ultrasonic inspection device and the destructive testing is very good. Further the comparison of both results (Figure 3) proves that not only the spot weld diameter is displayed correctly, also the D-scan picture of the spot weld is very close to the look of the real spot weld.

The deviations of the measurement for all 16 spot welds of this layer joint are shown in Table 2.

Table 2. Measurement results for layer joint acc. to table 1 no. 1

Count of welds	Average deviation	Max. deviation	Min. deviation
16	-0.35 mm	-0.7 mm	0.1 mm

These deviations are in the range of the physical resolution of 0.35 mm as well as within the repetition accuracy for the caliper measurement of ±0.2 mm.

2.3 Presentation of results for aluminium (2-layer joints)

The presentation of the results for layer joints of aluminium is based upon the inspection results according to no. 3 in the table 1, which are based upon a 2-layer joint.
Figure 4 shows a representative result for an ultrasonic inspection with the PHAsis[one] inspection device (Left) and the appropriate result of destructive testing (Middle).

Figure 4. representive result for aluminium (Left: ultrasonic inspection result; Middle: destructive testing; Right: manual change of ultrasonic inspection result)

The inspection results for this specific spot weld are as follows:
Spot weld diameter (PHAsis[one]): 4.7 mm
Spot weld diameter (destructive testing): 5.9 mm

The comparison of both results shows a deviation of -1.2 mm. The oval shape of the spot weld is shown by the PHAsis[one] ultrasonic inspection device and the destructive testing. By a more precise view on Figure 4 (Left) it is obvious that the automatic calculated ultrasonic inspection result is based on the smallest diameter of the oval shaped spot weld.

The comparison of the evaluated spot weld diameter by the PHAsis[one] inspection device with the result of the smallest diameter of the destroyed spot weld confirms the equality of the results:
Spot weld diameter (PHAsis[one]): 4.7 mm
Smallest diameter (destructive testing): 4.8 mm

A manual adjustment of the circle in the PHAsis device (possible to be done by the operator) leads to a result of 6.0 mm for the spot weld diameter as shown in Figure 4 (Right) with the dotted circle. This result correlates to the destructive testing.

The deviations of the measurement for all 6 spot welds of this layer joint are shown in in Table 3.

Table 3. Measurement results for layer joint acc. to table 1 no. 2

Count of welds	Average deviation	Max. deviation	Min. deviation
6	-0.1	0.8	0.0

These deviations are in the range of the physical resolution of 0.35 mm as well as within the repetition accuracy for the caliper measurement of ±0.2 mm.

2.4 Correlation for other inspection methods (CT and shear strength testing)

Further possibilities to compare the ultrasonic inspection results with other techniques are the correlation with the CT and with the shear strength testing. In the following this is shown according to no. 3 in Table 1.
Figure 5 (Left) shows the D-scan and an exemplary “good” A-scan for that spot weld.

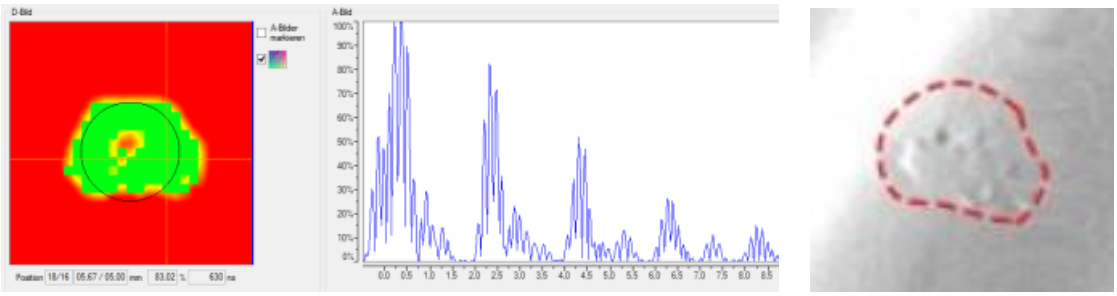


Figure 5. Left: Ultrasonic inspection d-scan incl. an exemplary a-scan; Right: CT image

The PHAsis[one] inspection device gives the following evaluation result:
Spot weld diameter (ultrasonic inspection): 4.6 mm
Figure 5 (Right) shows the same spot weld generated by a CT.

The comparison of both figures shows the good correlation for the shape of the spot. It also shows that the evaluation of spot welds by CT technology requires a trained evaluator. An absolute determination of the spot weld is only possible by a dynamic view on live CT. This absolute determination was not possible here using the CT image.

More significant results can be determined with the correlation of ultrasonic inspection and shear strength testing.

The following values are determined for spot weld diameter:
spot weld 1: 5.0 mm
spot weld 2: 1.3 mm

By shear strength testing the following values are determined for the maximum strength:
spot weld 1: 2470 N
spot weld 2: 557 N

By building the ratio of maximum strength and ultrasonic inspection result, the following formula (1)

$$shear\ strength = \frac{maximum\ strength\ in\ N}{spot\ weld\ diameter\ in\ mm}$$

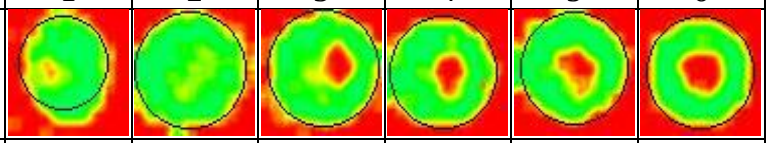
leads to these results:
spot weld 1: 494 N/mm
spot weld 2: 428 N/mm

This result proves a correlation between the evaluation with the PHAsis[one] ultrasonic inspection device and the stability of a spot weld.

3. Limits of ultrasonic inspection

Despite the good correlation between ultrasonic inspection results and several destructive testing methods also the limits and further the possible risks have to be addressed.
For visualization the inspection results of no. 4 in table 1 are used. The inspection was performed with a 2-layer joint.
The inspection results as shown in table 4 suggest that all spot welds are good because of the constant spot weld diameter.

Table 4. Measurement results for layer joint acc. to table 1 no. 4

Spot no.	1	2	3	4	5	6
Displayed result						
Measured Spot weld diameter by UT	6,7	8,3	8,3	8,0	8,0	8,0

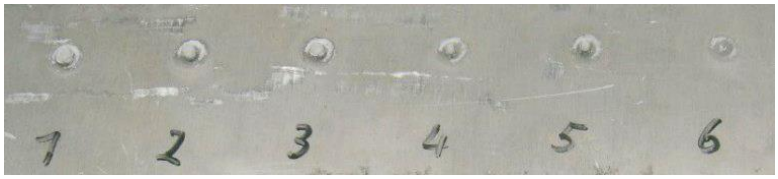


Figure 6. Destructive testing results for no.4 of table 1

The destructive testing confirms a continuous reduction of the spot weld diameters of Spot 1 – 6 see Figure 6.
Table 4 shows nearly constant diameters evaluated by the ultrasonic testing.
The ultrasonic inspection method is not able to detect adhesive areas of a spot weld.
A challenge that can be solved neither by "classic" ultrasonic inspection nor by modern Phased Array ultrasonic technology. The adhesive area is completely sound-permeable. No indications are shown in the A-scan and the spot weld is evaluated as a good spot.
Such "adhesive spot welds" are mostly found in prepared test samples when not using secured welding parameters of production lines. This leads to the conclusion that these adhesions might appear when forcing weld parameters to get small spot diameters within a test sample.

4. Conclusion

Despite the physical limit of the ultrasonic inspection method in case of adhesion the correlation of ultrasonic inspection results with other non-destructive and destructive testing methods shows the high reliability of spot weld testing with PHAsis^{one}.
This correlation applies for aluminium layer joints as well as steel layer joints.