INVESTIGATION OF THE QUALITY CHARACTERISTICS OF POLYAMIDE 12 PIPE WELDS

M. Eckes & Dr. B. Baudrit
SKZ – Das Kunststoff-Zentrum
Würzburg, Bavaria, Germany

Dr. M. Troughton & D. Wylie
TWI Ltd
Cambridge, Great Abington, UK

H. van Laak & J. Fritz
Evonik Resource Efficiency
Marl, North Rhine-Westphalia, Germany

SHORT SUMMARY

Two research institutes, the German Plastics Center (SKZ) and TWI, examined the established quality tests for welds in PA-U12 pipes. The aim was to investigate to what extent the current quality criteria are transferable to PA-U12. This includes destructive tests such as the technological bending test as well as non-destructive tests like phased array ultrasonic testing.

KEYWORDS

Polyamide 12, Butt Fusion, Electrofusion, Mechanical properties, Non-destructive testing

ABSTRACT

Unplasticized polyamide 12 (PA-U12) is increasingly being used in pipe applications, especially in the gas sector. However, the material behavior in the usual quality tests for pipe welds has not yet been thoroughly investigated.

For this reason, two research institutes, worked in cooperation with a manufacturer of PA-U12 to examine the established quality tests for pipe welds in PA-U12 pipes. Among the test methods were destructive test methods as well as ultrasonic inspection methods for non-destructive testing of pipe welds.

The results provide an insight into the assessment of the quality characteristics of PA-U12 pipe welds and will be used for the training of personnel as well as for the extension of international technical standards.

INTRODUCTION

Polyamide 12 is a high-performance polymer material with outstanding mechanical properties and excellent chemical resistance against many fluids. For decades it has been the preferred material for demanding applications, e.g. in the automotive industry for fuel lines in cars and for pneumatic brake lines in trucks. PA-U12 pipes have a considerably high internal pressure resistance, even at elevated temperatures and a low gas permeability. The extrusion of high molecular weight PA-U12 compounds into pipes and injection moulding, e.g. into fittings, is possible on standard processing machines.

For more than 15 years, PA-U12 has been investigated as a material for gas pipes. Up to 18 bar MOP (maximum operating pressure) PA-U12 pipes offer an alternative to steel pipes for use at operating pressures above 10 bar. The use of PA-U12 offers considerable cost savings, when passive and active corrosion protection measures can be omitted and when trenchless laying of the pipes from the coiled bundle is possible. In addition, as with the use of other plastic pipe compounds, a large part of the follow-up costs incurred with steel, e.g. for maintenance, are eliminated.

NOMENCLATURE

HM = Electrofusion socket welding (de: Heizelement-Muffen-Schweißen)
HS = Butt fusion welding (de: Heizelement-Stumpfschweißen)
LSV = Mechanical linear shear test (de: Maschineller Linearscherversuch)
PA-U12 = unplasticized Polyamide 12
PAUT = Phased Array Ultrasonic Testing
TOFD = Time of Flight Diffraction

EXPERIMENTAL

For the butt fusion (HS) joining process, the limits of the process window specified in DVS guideline 2207-16 [1] were investigated and the influence of the process parameters on the resulting bending angle was assessed. The bending behavior of PA-U12 HS joints was studied by welding pipes with different diameters (60. 110 and 160 mm). Specimens cut from the joints were tested using the technological bending test according to DVS guideline 2203-5. The measured values were compared with the requirements according to DVS 2203-1 supplement 3.

HM socket welds were tested using the mechanical linear shear test (Figure 1) according to DVS guideline 2203-6 supplement 1.

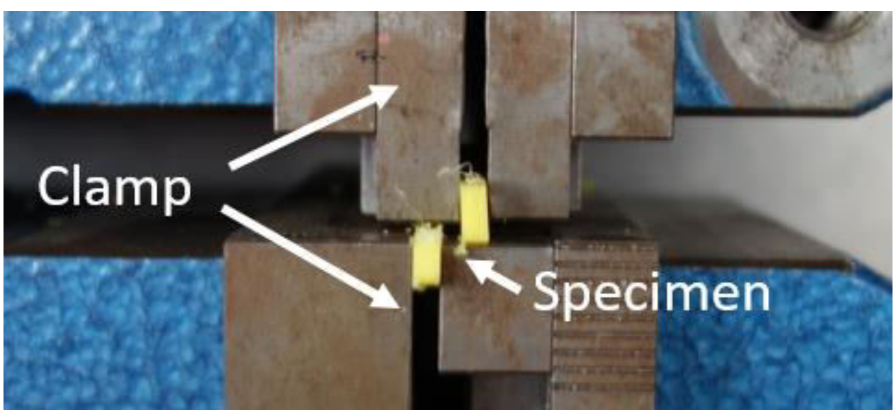


Figure 1: Mechanical linear shear test (LSV)

Additionally, non-destructive test (NDT) methods, were used to examine possible flaws in the welds. During the investigation, welds with practical relevant flaws were prepared. As part of the NDT, time of flight diffraction (TOFD) was performed on HS samples (OD 160 mm, SDR 11) from the DVGW [5] research project and phased array ultrasonic testing (PAUT) was used to inspect HM socket welds. To correlate the findings of the PAUT inspection with the mechanical properties, the inspected welds were also examined using peel decohesion tests according to ISO 13954 and EN 12814-4.

DISCUSSION

Butt Fusion (HS)

With the technological bending test the four corner points of the process window (HS) according to DVS 2207-16 were investigated. This includes high joining pressure and high temperature (0.3 MPa and 240 °C), and low joining pressure and low temperature (0.2 MPa and 220 °C). The parameters are summarized in Table 1.

Table 1: Process parameters HS welding

Test series	Hot plate temperature (°C)	Joining Pressure (MPa)
V01	240	0.3
V02	240	0.2
V03	230	0.3
V04	230	0.2
V05	220	0.3
V06	220	0.2

Figure 2 shows a summary of the achieved bending angles for different pipe wall thicknesses. For reference, the required minimum bending angle according to DVS Guideline 2203-1 supplement 3 is shown as a black line.

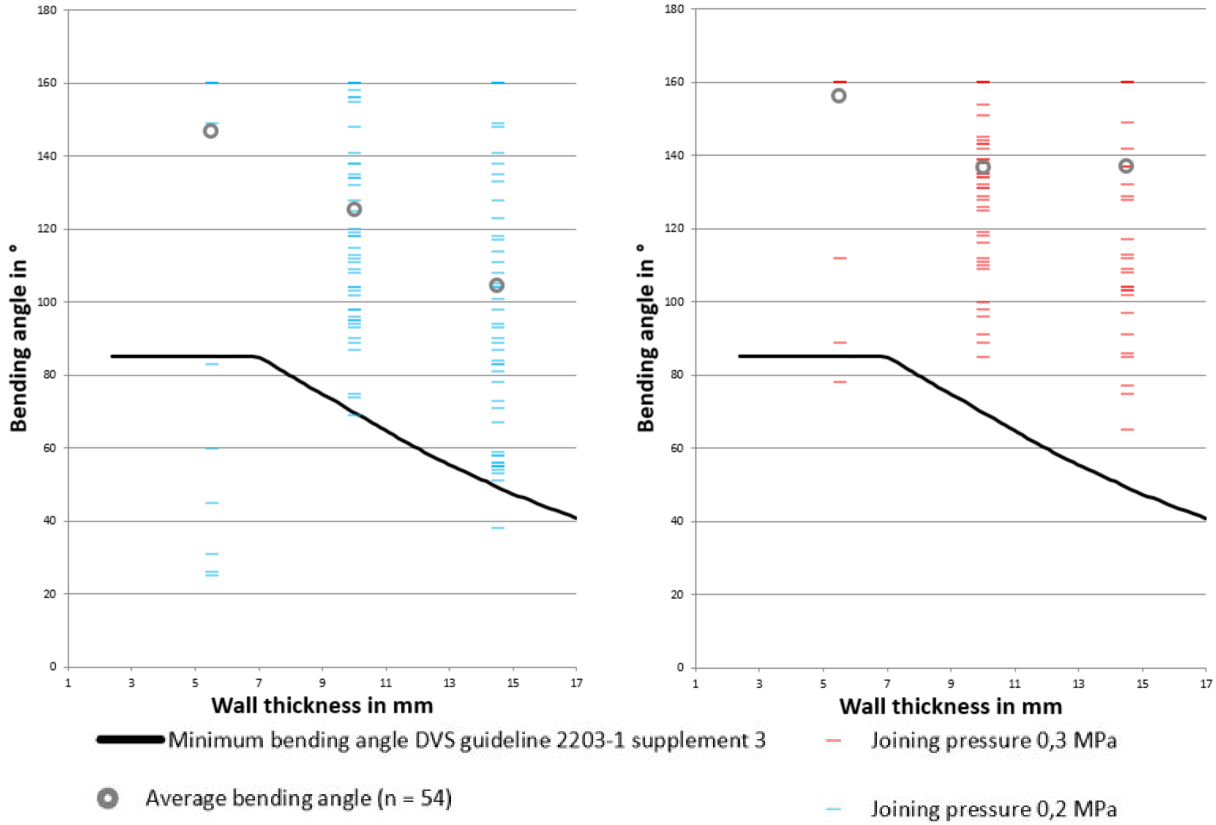


Figure 2: Bending angle of PA-U12 HS joints in comparison with DVS Guideline 2203-1 supplement 3

Overall, the values for PA-U12 are on average significantly higher than the minimum requirement according to DVS 2203-1 supplement 3.

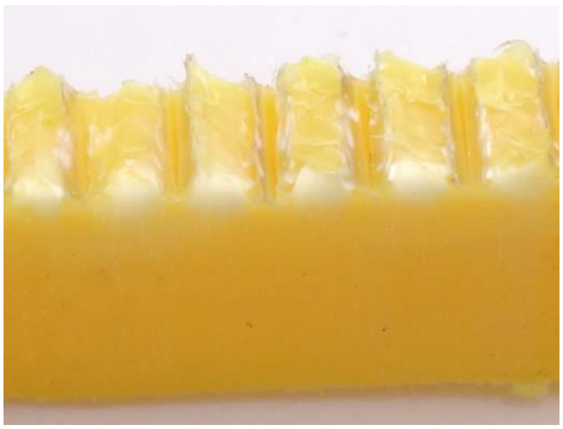
Some individual samples did not meet the minimum requirement. Those specimens that did not meet the required minimum bending angle were predominantly welded with the low pressure of 0.2 MPa. With an increase to a welding pressure of 0.3 MPa the weld quality significantly increases (using t-test with a significance level of $\alpha = 5$ %) for the wall thickness of 10.0 and 14.5 mm. The positive effect of an increased joining pressure has already been demonstrated by the DVGW project GW 201716 [5] about NDT methods for the use on site for the evaluation of HS welded joints. So, during ongoing harmonization for the HS welding of PA-U12 pipes in ISO standards and DVS guidelines the minimum jointing pressure will be raised by 0.05 MPa, as shown in Table 2.

Table 2: Ongoing harmonization of jointing pressures for HS welding of PA-U12 in ISO and DVS standards

Standard		***DIN EN ISO 16486-5***		***DVS 2207 -16***	
publication (edition)		*2012 (first)*	*2021 (second)*	*2010 (first)*	*Request for revision*
jointing pressure	*range*	*0.3 ± 0.1 MPa*	*0.3 ± 0.05 MPa*	*0.25 ± 0.05 MPa*	*0.3 ± 0.05 MPa*
	Min.	*0.2 MPa*	*0.25 MPa*	*0.2 MPa*	*0.25 MPa*

<u>Investigation of the optimal fusion gap for electrofusion sockets (HM) using the LSV (at SKZ)</u>

Shear tests examine the quality of a welded joint produced by the HM process. The tests induce a fracture in the joint plane between pipe and socket, followed by an evaluation of the fracture pattern. The fracture surface that results from a shear test refers to the area between the first and last turn of the heating coil in each welding zone. Figure 3 shows an example of the ductile and brittle fracture areas. To evaluate the fracture surface, the proportion of brittle fracture and other defects such as voids was measured as a percentage of the total joining zone length (DVS 2203-1 supplement 4).



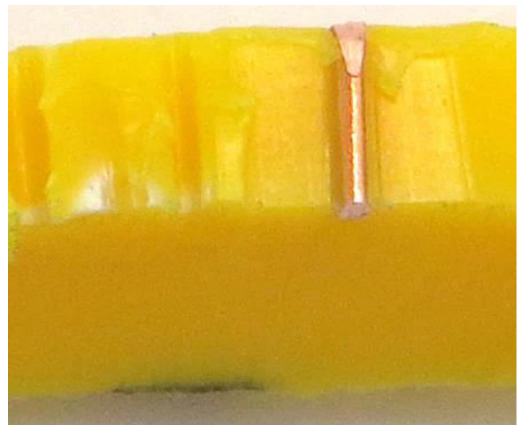


Figure 3: left: ductile area of the fracture surface after LSV testing,
right: Brittle area of the fracture surface after LSV testing

Like polyethylene pipes, polyamide is also scraped before welding via HM. DIN ISO 16486-5 (First Edition 2015) [2] recommends the thickness of the chip produced by the scraping process to be >=0.2 mm. In general it is not necessary to scrape a PA-U12 pipe other than for cleaning the surface due to its high UV resistance, the low potential for surface damages combined with the high resistance against slow crack growth [3, 4]. However, contracting parties should agree on how to deal with scraping based on a verification of the resistance against UV, impact and SCG of the corresponding PA-U12 gas pressure pipe resin.

To determine the optimal fusion gap between the pipe and the coupler multiple variations between 0.10 and 0.91 mm were produced. The fusion gap is defined as:

$$\Delta R = \frac{Inner\ diameter(coupler) - Outer\ diameter(scraped\ pipe)}{2}$$

Figure 4 shows the mean values for shear strength in correlation to the fusion gap. A fusion gap between 0.10 and 0.74 mm resulted in a high average shear strength between 35 and 29 MPa. With an increasing fusion gap (≥ 0.8 mm) the values for the shear strength drop to an average of 22 MPa.

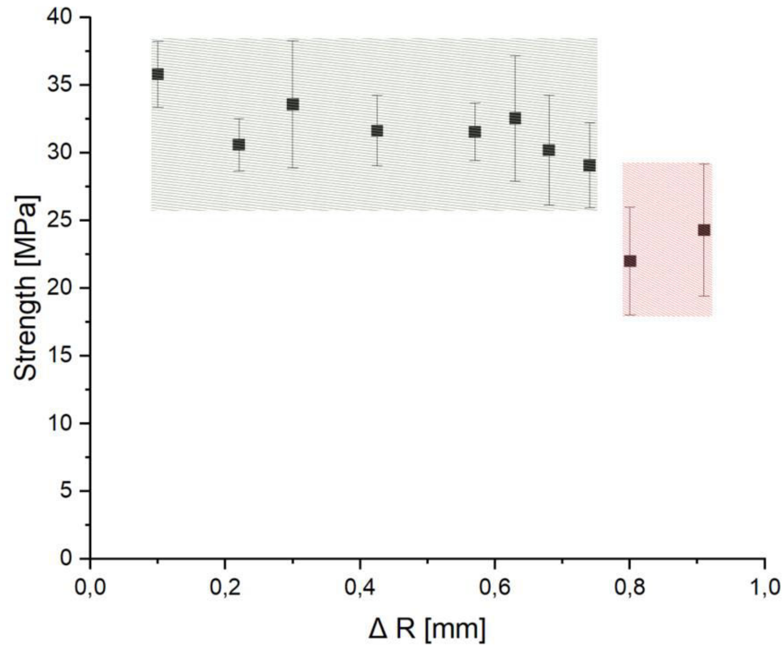


Figure 4: Average shear strength in correlation to the fusion gap

Figure 5 shows the evaluation of the fracture surface in comparison to the minimum value of ductile fracture (horizontal red line) according to DVS 2203-1 Supplement 4. In correlation to the shear strength the percentage of ductile fracture also decreases with an increasing fusion gap. The brittle fracture was always located between the first and the last two turns of the heating coil. This area coincides with the zone where the least heat energy is introduced during the joining process.

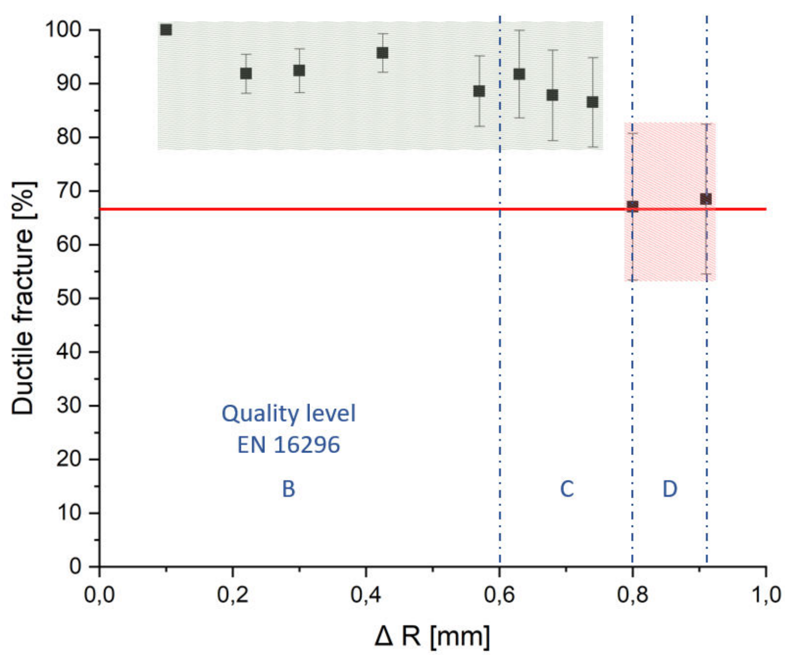


Figure 5: Evaluation of the fracture surface in comparison to the minimum values of ductile fracture according to EN ISO 16486-3 Table 4 (horizontal red line) with correlated quality levels for voids according to EN 16296 (see Table 3).

The formation of voids in the welding zone could first be observed with a fusion gap of 0.57 mm. With an increasing fusion gap, the occurrence of those voids also increased. It was observed that voids always form centered around the heating coil. According to the minimum value of ductile fracture specified in DVS 2203-1 Supplement 4 the occurring imperfections are acceptable until a fusion gap of 0.8 mm is reached. Additionally the formation of voids was assessed as quality levels according to EN 16296 (see Table 3) and can also be seen in Figure 5, where it can be seen that Levels B and C are acceptable in terms of the ductile fracture criterion. An example of Level D voiding is shown in Figure 6.

Table 3: Definition of quality levels 1 for electrofusion socket welds (EN 16296)

Designations	***Level B***	***Level C***	***Level D***
Gas cavity	*Permissible if diameter of largest cavity ≤ 5 % of fusion zone length and sum of all cavities ≤ 10 % of fusion zone length at any position around the circumference*	*Permissible if diameter of largest cavity ≤ 10 % of fusion zone length and sum of all cavities ≤ 25 % of fusion zone length at any position around the circumference*	*Permissible if diameter of largest cavity ≤ 15 % of fusion zone length and sum of all cavities ≤ 33 % of fusion zone length at any position around the circumference*

Figure 6: Formation of voids (fusion gap 0.80 mm, specimen with the highest number of voids).

<u>Investigation of nondestructive detection of weld flaws using the PAUT and TOFD (at TWI and Avacon)</u>

As a non-destructive test method, PAUT was used by TWI to examine possible flaws in the HM welds. The PAUT procedure used was based on the procedure developed for inspecting EF joints in PE100 and the system was calibrated for material velocity, wedge delay and sensitivity using a PA-U12 calibration block, designed and manufactured specifically for this test (Figure 7).

[1] For specific applications, some requirements more stringent than level B might need to be prescribed and shall be defined between the contracting parties as quality level A.

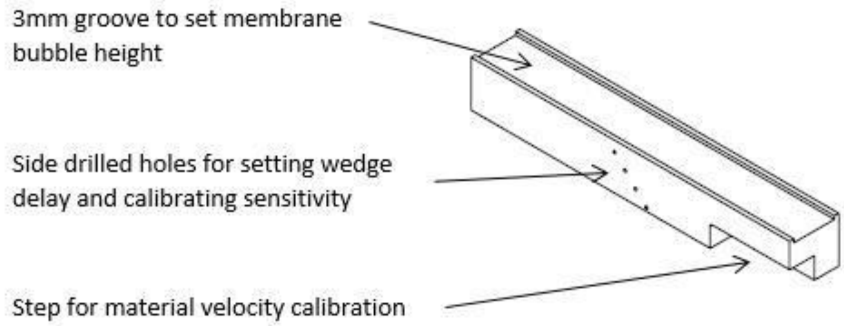


Figure 7: Calibration block for PAUT of PA 12 EF joints (image copyright © TWI Ltd, reproduced with permission).

Various welding flaws such as voiding and lack of fusion were successfully detected with this test method. For example, an area of the fusion zone containing voids can be seen in the PAUT image shown in Figure 8, where indications of voiding can be seen around the heating wire (in the red square).

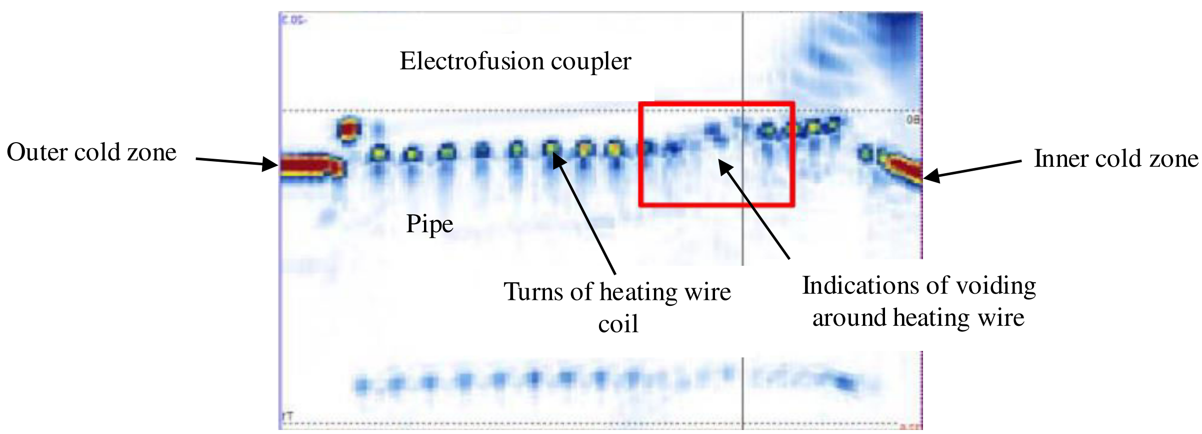


Figure 8: PAUT image of an HM joint (image copyright © TWI Ltd, reproduced with permission).

To correlate the findings of the PAUT inspection with mechanical tests results, the inspected welds were subsequently subjected to peel decohesion tests according to ISO 13954 and EN 12814-4. During the first tests, to ISO 13954, all the specimens failed through the parent pipe, as shown in Figure 9. Although this shows that these welds meet the requirements in ISO 16483-3 for qualifying HM joints in polyamide pipe, in order to get a correlation between the NDT and destructive tests, a peel test was required that would generate failure through the weld interface.

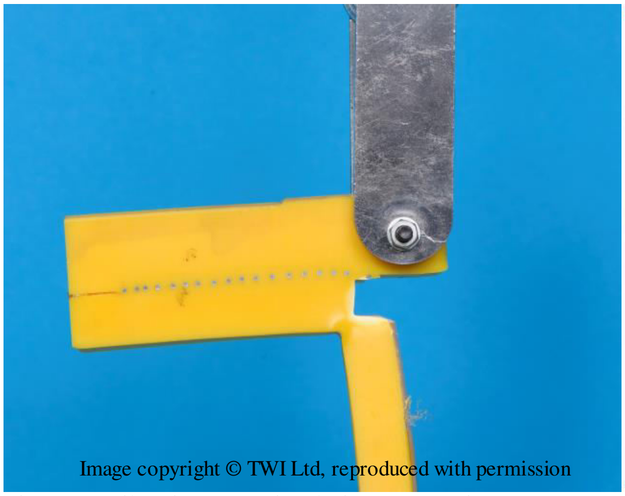


Figure 9: Failure in parent pipe during ISO 13954 test.

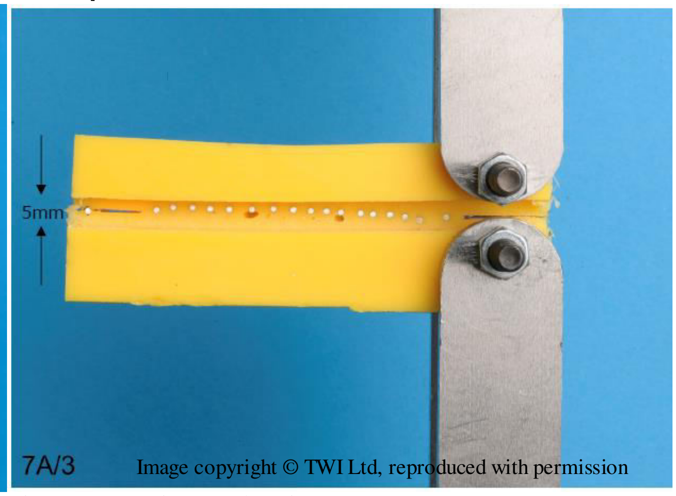


Figure 10: Specimen and testing setup to EN 12814-4.

It was therefore decided to take the remaining ISO 13954 specimens and modify them so that they conformed to the EN 12814-4 specimen geometry (Figure 10). This involved reducing the width of the specimen to 20mm and machining a 5mm wide groove to a depth of 5mm either side of the specimen, cutting the pipe section square with the edge of the coupler, and drilling 5mm holes in both the pipe and fitting to facilitate separation during the test. With the modified specimen geometry and testing procedure, a mechanical failure within the joining zone could be generated (Figure 11).

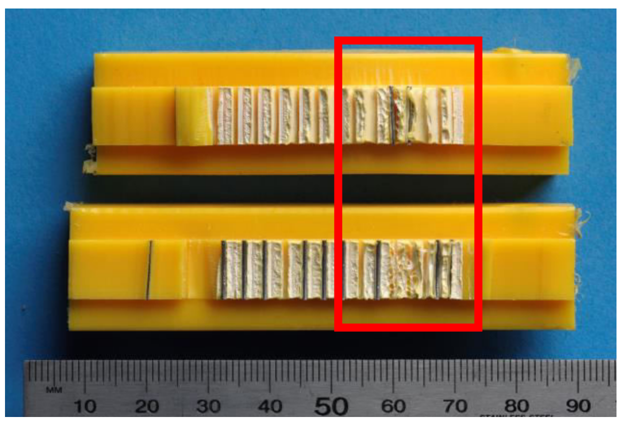


Figure 11: Fracture surface of specimen conforming to EN 12814-4, with the area of voiding marked by the red rectangle (image copyright © TWI Ltd, reproduced with permission).

The specimen shown in Figure 11 was from the same HM joint and at the same circumferential position as the PAUT image in Figure 9, and it can be seen that the area of voiding in the PAUT image correlates very well with the area of voiding in the fracture surface from the peel decohesion test.

Even though the peel test in accordance with ISO 13954 is specified in ISO 16486-3 for qualifying HM joints in polyamide pipes, it does not generate failure through the weld interface, even if the cross-sectional area at the interface is reduced by 50%. The peel test in accordance with EN 12814-4 is a much more demanding test and is capable of generating failure through the weld interface in PA-U12 HM joints.

The HS welds from GW 201716 were tested at Avacon using the TOFD method (Figure 12), where the testing device (Sonotest veo 16:64) was calibrated using a PA-U12 calibration block. Here too, various flaws caused by deviating welding parameters could be found. With both ultrasonic tests, similar indications have been found in PA-U12 compared to polyethylene.

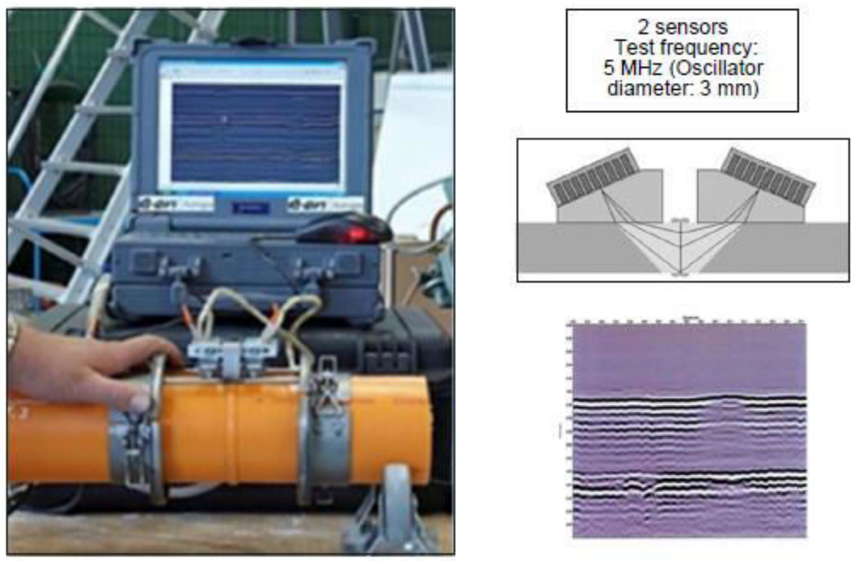


Figure 12: Procedure of the TOFD examination (Picture provided by Avacon)

CONCLUSIONS

The results of the technological bending test show the material is generally easy to HS weld. In individual cases, a test specimen of a welded joint did not achieve the minimum bending angle or ram displacement (bending way) acc. to DVS. However, the welds with the lowest bending angles were predominately located at the lower end of the process window (220°C and 0.2 MPa). All welds at the upper end of the process window (230-240°C and 0.3 MPa) were above the minimum requirement according to DVS 2203-1 supplement 3. A significant influence of the joining pressure is shown here.

In the LSV all specimens met the requirements of DVS 2203-1 with regards to the flawless percentage of joining zone length of 66,6 %.

The results of the shear tests show that PA-U12 meets all quality standards when welded with a fusion gap between 0.1 to 0.74 mm. A fusion gap greater or equal 0.8 mm causes the formation of bigger voids and decreases the mechanical strength as well as the percentage of ductile fracture below the required value. In respect to the low number of investigated HM welds, the test results gives an indication that fusion gaps lower or equal to 0.74 mm lead to an acceptable quality and lower or equal to 0.6 mm effect a high quality.

When calibrated on PA-U12 material, the PAUT of PA-U12 HM joints gives comparable results to the data quality obtained when scanning polyethylene HM joints, with wires, cold zones and pipe inner wall clearly visible in the scan data on a good HM joint.

ACKNOWLEDGMENTS

We would like to thank Mr. Weßing (Avacon) for the project coordination in GW 201716 and NUPI Industrie Italiane for providing their expertise and products for research purposes. NUPI Industrie Italiane provided all electrofusion sockets for the investigation of the fusion gap.

REFERENCES

[1] DVS 2207-16 Welding of thermoplastics - Heated tool welding of pipes and piping parts made of Polyamide 12
[2] ISO 16486 series, Plastics piping systems for the supply of gaseous fuels – PA-U piping systems with fusion jointing & mechanical jointing; already harmonized as EN ISO 16486 -1: General, -2: Pipes and -3: Fittings; harmonization ongoing for ISO 16486 -4: Valves and -5: Fitness for purpose of the system
[3] H. van Laak, J. Heimink, M. Messiha, A. Frank, C. Bruckner und T. Kratochvilla, „Why PA-U12 high pressure pipes do not care about "ROCK ´N´ SHARD" in view of pas 1075," in Proceedings of the 20th Plastic Pipes Conference, Amsterdam, 2021.
[4] H. van Laak, J. Heimink, M. Messiha, A. Frank, C. Bruckner und T. Kratochvilla, „Polyamide 12 for Gas Piping Systems with MOP 16/18 bar" in 3R Special 01, 2021.
[5] M. Eckes, B. Baudrit und W. Weßing, „Forschungsbericht GW 201716 – Zerstörungsfreier Integritätstest für stumpfgeschweißte Kunststoffrohre auf der Baustelle – Bead-Bend-Back-Test," DVGW Deutscher Verein des Gas- und Wasserfaches e. V., Bonn, 2020.
[6] S. Willis, Feasibility Study for PolyTest on PA 12 EF Joints – Mechanical Testing of Flawed Joints, TWI Report 31717/1v2/18 (not published)
[7] D. Wylie, PAUT Analysis Report for PA-U12 Electrofusion Welds in d110 mm Pipe, TWI Report 31457/1v5/17 (not published)

