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Non-destructive methods of quality assessment of permanent joints of polymer materials

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ABSTRACT

Purpose: The purpose of the research was the verification of usefulness of selected non-destructive testing methods as tool of assessement of permanent joints of elements with variable thickness and geometry.

Design/methodology/approach: The research was conducted with the use of samples prepared from the components used for strengthening the car seats. The elements were made from low-density polyethylene, applying the injection technology, and then butt welded. The quality assessment was conducted with the use of selected non-destructive methods - visual, thermal imaging, shearography inspection and 3D scanning. In order to verify the quality of the welds, tensile strength tests were conducted.

Findings: The research conducted will indicate, within the researched scope, the method, which allows the identification of flaws of permanent joints.

Research limitations/implications: Within the frame of the work we limited ourselves to the analysis of geometry of weld performed with the application of the method of butt welding. The exact assessment of quality of the joints performed requires additional tests which take into account the properly welded comparative samples and other non-destructive methods.

Practical implications: The application of non-destructive methods of quality assessment, particularly spatial scanning, allows the assessment of quality and exact dimensioning of flash both from outside (visible) and outside of the element.

Originality/value: The work presents the innovative application of spatial scanning 3D for the assessment of flash geometry achieved as the result of butt welding.

Keywords: Polymers; Engineering materials; Strength tests; Non-destructive testing methods

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1. Introduction

The selection of appropriate kind of joints with reference to machine parts, articles of everyday use or responsibility elements of constructions made of polymer materials is quite a complicated process. We should take into consideration a number of factors, among others, a kind of load, working environment, geometry of a product and material. Two groups of polymer construction materials joints are distinguished. These are temporary and permanent joints. Their division is shown in Fig. 1.

The presented paper is devoted to permanent joints, with the special emphasis on the process of frontal hot welding (otherwise known as "front heat sealing" or "butt welding") of thermoplastic polymer materials.

It should however be stressed that the methods of welded and heated joints are only applied for joining the thermoplastic polymer materials, while the hardened materials could be joined by other ways.

In case of joining processes, appropriate preparation of joined surfaces is of great importance, e.g. through sanding, cleaning or degreasing. It refers to all permanent methods.

Glued joints are applied to both thermoplastic polymer materials and to hardened ones. Glueing is a process which is made possible thanks to adhesion, which means the grip and the internal cohesion. Adhesion is conditioned by surface tension and the presence of highly polar groups in the polymer.

The lower the surface tension, the better wettability, and as a final effect, a better connection. Cohesion, in turn, is conditioned by molecular weight of gluing substance. Together with the increase of molecular weight, the cohesion also increases.

Depending on physical and chemical properties the following glues can be distinguished:

- solvent based (binding by solvent evaporation),
- fusible (binding by solidification of melted adhesive mass),
- hardening (thermosetting and chemically hardenable).

The endurance of glued joints depends on the kind of glue, mechanical loads operating on a joint (detachment, cutting, and tearing off) and a type of connection (frontal, overlapping, overlaying). The most durable are the joints working on the shearing stress.

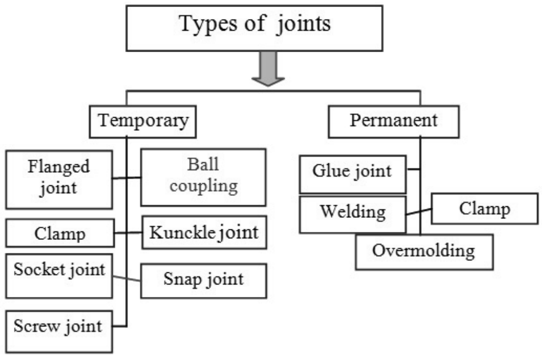


Fig. 1. Types of joints [1]

Welding and heat sealing is only possible for thermoplastic polymer materials, thanks to the phenomenon of diffusion, which means the mutual intertwining of polymer chains, resulting from providing heat to the system as well as the stress impact. Heating up of the joined surfaces several dozen degrees above the melting or flowing temperature, increases the macromolecules movement to such an extent that their displacement and strong rapprochement is possible. Achieving the proper quality connection is possible thanks to:

- proper structure of macromolecules,
- viscosity of polymer material in the welding temperature,
- temperature of joined surfaces,
- unit pressure,
- time of individual phases of the process,
- preparation of joined surfaces.

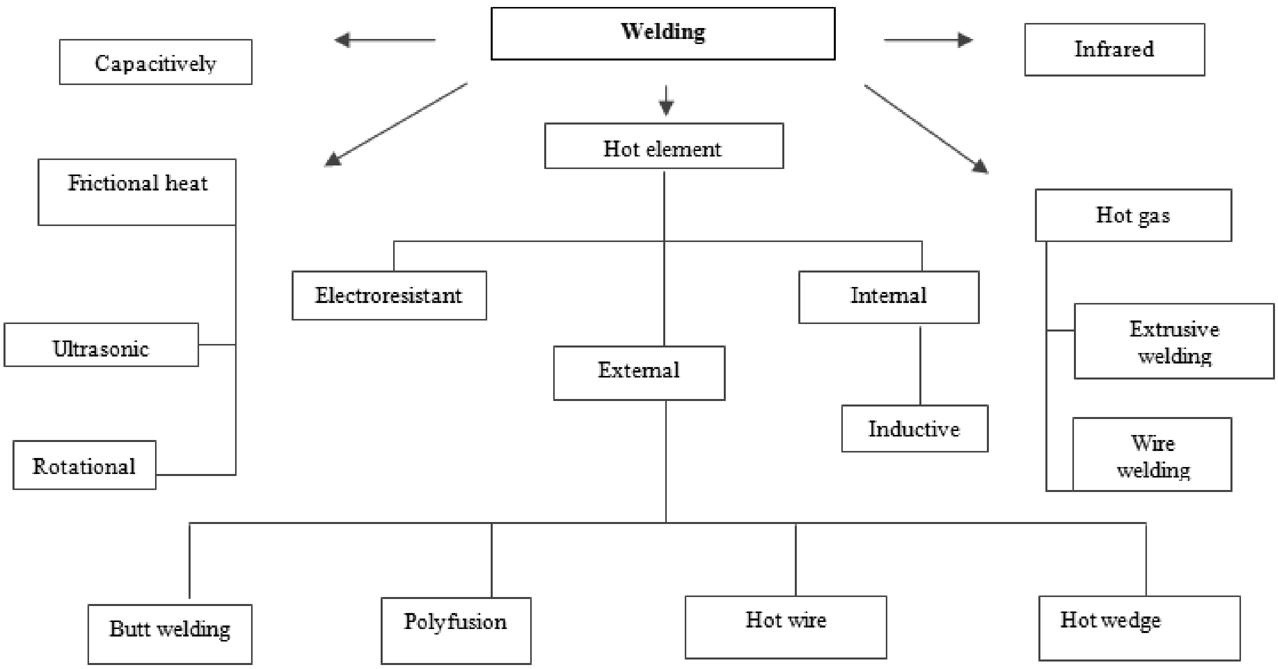


Fig. 2. The division of welding and hot welding methods with reference to the way of heat provision to the system [2]

Heat might be supplied to system through:

- radiation (eg. ultrasonic welding),
- convection (eg. welding),
- joint (eg. butt welding).

The division of methods with reference to the way of heat provision is presented in Fig. 2.

The choice of appropriate joining method is conditioned by thermal and electrical properties of the polymer material as well as the geometry of joined elements. For instance, hot welding with a hot wedge is applied to joining of foils and plates, frontal hot welding for pipelines, frictional welding for fuel filters or tanks and ultrasonic for small details. As far as welding is concerned it is applied for joining thick-wallet components made from polyolefins eg. tank, joint of floorings etc.

1.1. Frontal hot welding

Within the presented work we conducted the assessment of the welds made with the use of the method of frontal hot welding. It is the process in which properly prepared surfaces of welded elements are plasticized with the application of hot plate and after that are cooled. Heating and cooling are done under the pressure. The process parameters depend on the geometry of the joined element. The stages of frontal welding process are shown in Fig. 3.

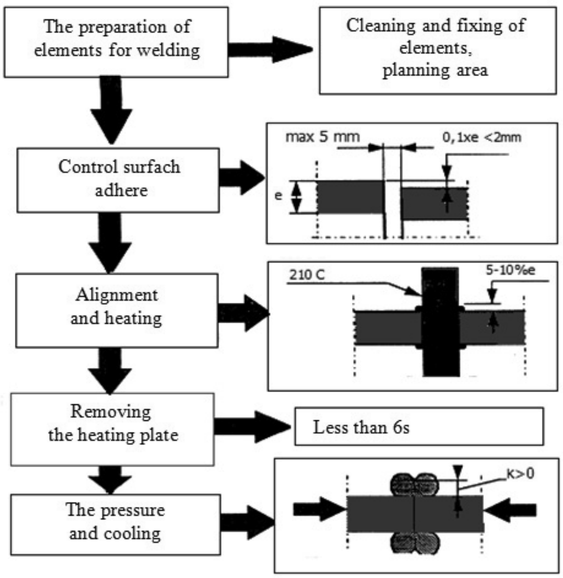


Fig. 3. Stages of the frontal hot welding process [2]

The process of frontal hot welding is conducted in some phases:

t1. surface levelling, is time in which the heating plate is situated between the two connected elements; this phase lasts until the flash from 5 to 10% of the thickness of the welded elements is obtained,

t2. heating, is time of plasticizing of elements surfaces, it is calculated in dependence of 10 sec. for each millimeter of welded parts' thickness,

t3. a pause lasts for about 6s and then the heating plate is removed from the system,

t4. time of pressure buildup - 1 sec. for each millimeter of welded parts thickness,

t5. cooling time - 1,5 min for each millimeter of welded parts thickness,

t6. time of joint quality verification - 8 min. For each millimeter of welded parts thickness.

The diagram of frontal welding process course is presented in Fig. 4, where t1, t2, t3, t4, t5, t6 stand for duration of individual welding phases.

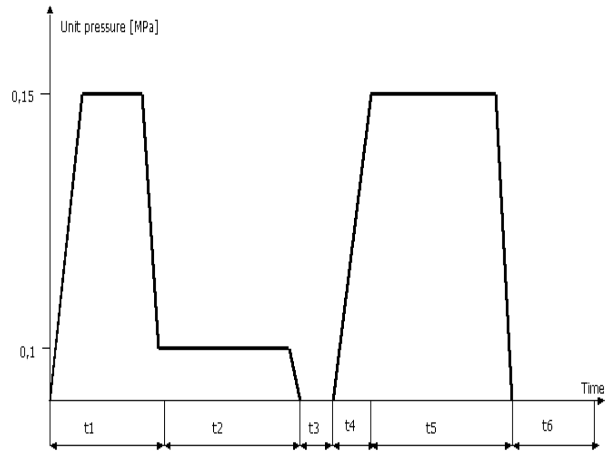


Fig. 4. Phases of frontal welding process [3]

The quality of obtained joints is influenced by many factors both the material ones and connected with the process itself. Badly selected input materials or process parameters lead to flaws, in the extreme cases even to lack of joints. What is important then is the assessment of the welds quality.

The quality assessment might be conducted in many ways. The most popular is the organoleptic method, which consists of visual inspection of the flash with the particular focus on uniformity of the distribution, width and height. The next method are endurance tests - tensile tests, bending and cutting. The flaws in the shape of bubbles are spotted with the use of eg. ultrasounds or radiography.

1.2. Non-destructive research methods

According to the research conducted [4-6, 10, 14, 17] the assessment of joint quality with the use of non-destructive research methods is also possible. Apart from already mentioned ultrasounds and radiography, among others, we can add, thermography, shearography, 3D scanning or penetrating and visual tests.

The Division of Metal and Polymer Materials Processing has been dealing in non-destructive methods of polymer materials diagnostics for many years particularly focusing on composites with hardened [6-9, 11-14] and thermoplastic matrix [16].

Visual research allows detecting material flaws of elements, which are predominantly surface raptures, leaks, hollowness's, uneven strenghtening of fibre layout or changes of colour scheme. They enable detecting discontinuities of material surface. As well as this it is also possible to detect fissures with depth of about 0.1 mm, and width of about 0.01 mm [6]. Such research can be conducted directly (with so called "non-armed eye, Fig. 5) or indirectly with the use of e.g videoscopes or endoscopes.

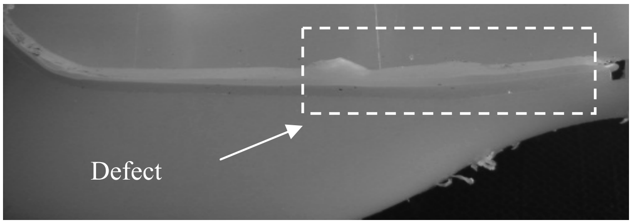


Fig. 5. Assessment of joint quality with the visual testing method

Penetration testing consist of setting a penetrating agent into a fissure and observing in daylight or UV light. Penetration testing conducted in UV light provide higher sensitivity, which enables identification of surface (with the width from 0.5 µm up to 10 µm, and the depth from 20 up to 200 µm). Penetrating agent might be aqueous, water-washable, emulsified or fluorescent preparations.

Ultrasonic testings (Fig. 6) allow detection of internal, superficial and over superficial flaws [1,18]. They are applied for both detecting flaws throughout the course of processing, joining and objects exploitation.

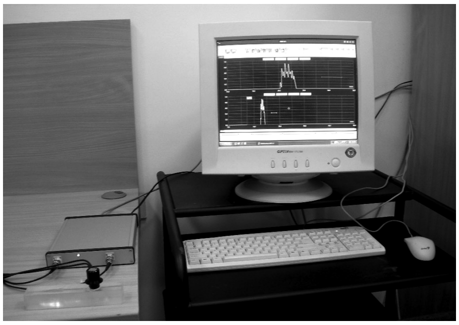


Fig. 6. Assessment of material quality with the use of ultrasonic testing method [9]

It should be stressed however, that the identification of a given kind of flaws is conditioned by the kind of wave applied and distinguishes the following methods:

- echo, which is based on reflection of waves of elements surface and of objects discontinuity;
- passing through (shadow) based on overshadowing a wave beam through discontinuities;
- TOFD, which takes advantage of diffraction deflection and dispersion of ultrasonic waves.

These methods are used for detection and identification of flat fissures, microfissures, bubbles of air, and contamination (echo). Shadow method is applied for examining thin elements; it does not allow the localization of a flaw but it makes it possible to assess its dimension. The last TOFD method enables identification of flat flaws (eg. fissures), inclusions, dissections and allows determining the exact hight and length of flaws.

Radiological research (Fig. 7) allows detecting internal, superficial and over-superficial flaws, particularly spacious discontinuities, bubbles, hollows, shrinkage and cavity fissures, inclusions and the changes in the thickness of elements and coatings [5]. Three radiological methods can be distinguished, i.e. tj. radiographical, radioscopic and radiometric. As a criterion of this distinction we assumed the one applied ionizing radiation detector and the resulting image. However it should be stressed, that within the industrial practice the most commonly applied is the radiographic method, which is based on two kinds of radiation: X-ray - X (radiography) and gamma - (gammography). The identification of flaws is much higher when X radiation is applied.

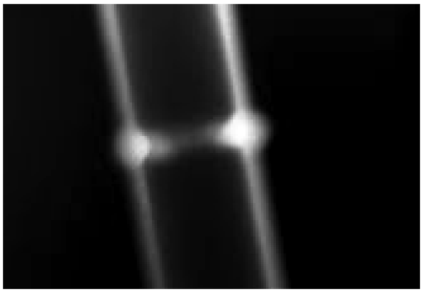


Fig. 7. Assessment of joint quality with the use of radiographic method [19]

The shearographic method enables detection of elements damages or flaws in the shape of air bubbles, presence of odd materials, fatigue cracks, dissections, subjected to loads. It is one of interferometric methods, taking advantage of laser light for deformation imaging in material subjected to mechanical loads. The image is achieved as a result of interference of dispersed laser beam on the surface of examined detail. The number of stripes grows together with the growth of deformation. Fig. 8 shows the scheme of measurement system and a model image.

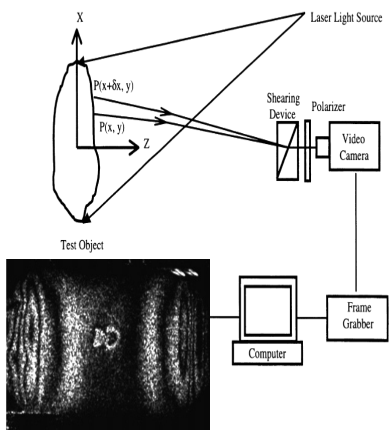


Fig. 8. Scheme of a system for the material quality assessment with the use of shearographic method [4,14]

Thermal imaging testing embrace the observation of infrared radiation emitted by any body with the temperature above absolute zero with the use of thermal imaging camera. Scanning and visualization of the field of temperature field with thermal vision camera allows the identification of objects and devices technical flaws. According to the way of stimulating object by a thermal impulse, we distinguish the method of passive thermography, in which the object is not stimulated by any additional thermal impulse and the active one where the basis is the thermal analysis of stimulated material response through the external thermal impulse. Fig. 9 shows the scheme of the working station for thermal vision within the frame of the research project [21].

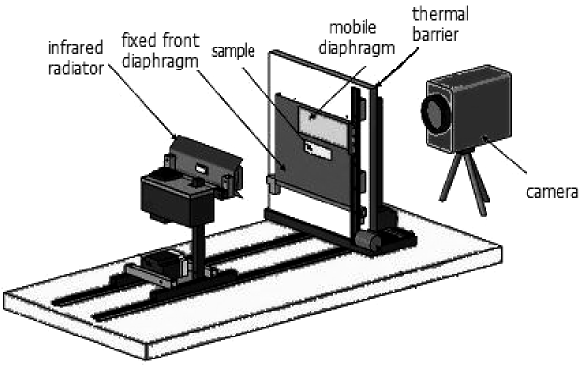


Fig. 9. Model working station for thermal vision research with the use of the method of active thermography [21]

Scanning the object with the use of 3D camera allows the flaws verification in the system of complex geometry. On the basis of the image we can compare the real measurements with the nominal ones, assess the shape e.g. a flash from both internal and external side of the object. It is of significant importance in case of systems of complex geometry, where the assessment of joint quality without destruction is required. Fig. 10 shows a modern system for 3D analysis which is designed for quality control of small and middle-sized parts made of polymer materials or metal.

Fig. 10. System COMET L3D [20]

Non-contact measurement allows scanning the objects of complex geometry in much shorter time than in case of conventional measurement tools or touch sensors.

2. Experimental

The aim of the research was the usefulness verification of selected non-destructive research methods and the instrument of assessment of quality of non-separable elements of complex thickness and geometry.

2.1. Research

The element of complex geometry and thickness was subjected to research conducted with the use of injection method and then frontally welded. It was the element made of polyethylene of mid density applied in automotive industry as strengthening of a car seat. The subject of research is shown in Fig. 11. with the area of joint quality verification marked. The quality assessment was conducted due to tightness and uniformity of the weld.

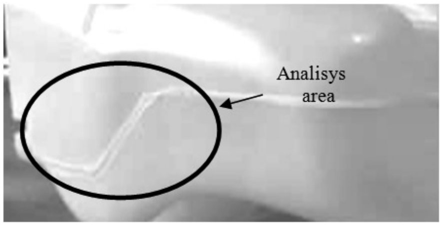


Fig. 11. The subject of research

Non-destructive research of the whole element was conducted with the use of four methods in the order:

- visual,
- thermography,
- shearography,
- 3D scanning.

Non-destructive testing have been compared with the strength of the connections, specified in a tensile test.

Visual research

Within the frame of visual research we noticed non-equal flash at the full length of the weld, displacement of welded elements in relation to both itself and the places where the lack of joint can be observed. Fig. 12. The hight measurement of the flash was conducted with the use of electronic caliper Mitutoyo to 250 mm with accuracy up to 0.01 mm, with results presented in Table 1. The areas in which flaws were noticed were subjected to the next non-destructive research.

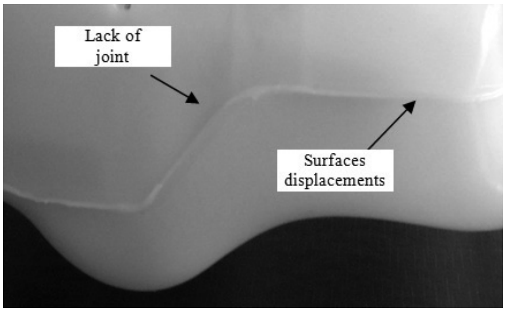


Fig. 12. Visual test

Thermovisual research

In order to determine the exact location and identification of flaws the thermovisual research was conducted. Thermal imaging camera FLIR A600 was applied together with software IrNTD which allows the full thermographic analysis of registered sample image, which was heated by a halogen lamp for 1s and the change in temperature in time was registered. The surrounding temperature 20°C and emissivity factor 0.92. Working station scheme is presented in Fig. 13.

The camera is equipped with a detector whose matrix has a resolution of 640 x 480 pixels. It is characterized by reduced resolution, which gives the possibility of achieving high frequency of thermograms registration even up to 200Hz as well as high sensitivity (fewer than < 50 mK).

IrNDT software is a system used for steering, registration and analyses of achieved image. It is applied for researching composite materials, quality control of the leather, testing aircraft sheathing, control of micro-crack in wheels and turbine blades, quality control of laser welds, detecting corrosion under a coat of paint and control of glued joints. It allows the application of various inducing methods, i.e. optical, ultrasonic, rotational currents, laser or halogen.

Sherography

As it has already been mentioned sherography allows the identification of flaws through deformation imaging. Within the work the analysis of joint quality was conducted with the use of apparatus ISIS 3100. Block diagram of the working station is presented in Fig. 14.

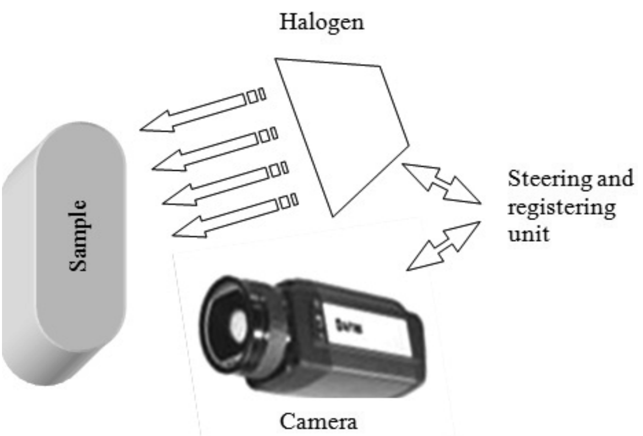


Fig. 13. Block diagram of the working station for thermovision research

Apparatus ISIS 3100 is equipped with two laser diodes, heating lamp, wide-graphic system with phase shift, CCD camera and ISISplus software.

The research was conducted with co-operation the ECtest Systems company from Cracow, which made apparatus ISIS 3100 available for conducting analyses.

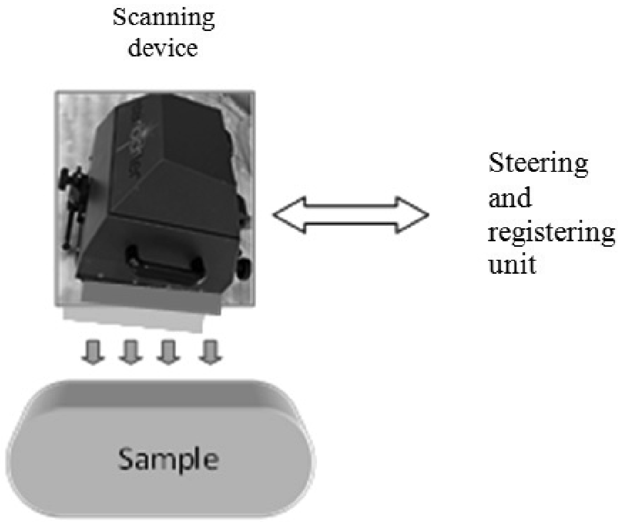


Fig. 14. Block diagram of the working station for measurement by sherography method

3D scanning

Within the frame of the present work we took advantage of the system Comet L3D by Steinbichler Vision Systems, Inc. presented in Fig. 10 in chapter 1.2. The system allows bilateral imaging of permanent connection, through the flash visualization. Technology COMET L3D uses LED light, which enables quick scanning, (within the time of 1.5 s) even up to 2 million of 3D measurement points. The system is equipped with a rotary table and a steering and a registering unit.

Strength research

In order to verify the results, a strength test on tensile of samples cut out of moulded part was conducted. The samples were cut out of randomly selected 10 points on the circuit of three various elements. However, it should be notified, that part of the samples was rejected before the tests, because the weld performed turned out to have been faulty. Fig. 15 shows the samples prepared for tests.

The tests for tensile strength were carried with the use of machine Zwick/Roell Z020 located in the laboratory of Institute of Engineering Materials and Biomaterials of Silesian University of Technology, Gliwice, Poland, in accordance with the standard PN-EN ISO 527 - 1 [22]. Tests were performed in the following conditions:

- tensile speed 50 mm/min,
- temperature 22 ± 2°C.

During the test set:

- tensile strength [MPa] - σ_M,
- break strength [MPa] - σ_b,
- young's modulus [MPa] - E,
- tensile strain [%] - ε_M,
- break strain [%] - ε_B,

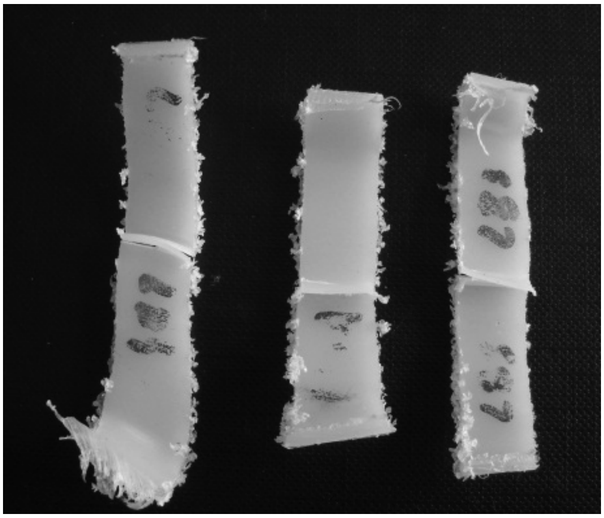


Fig. 15. Preparation of a sample for tensile strength tests

3. Results and discussion

3.1. Visual research

The diagram (Table 1) juxtaposes the width of the flash in various places of the circuit of the tested element. The width tolerance cannot exceed ±10% of the average value of the width, and the total width should remain within the range from 0.7 up to 1.0 of the thickness of the element wall [2]

Table 1.
Juxtaposition of the height of the flash on the element circuit

Measurement point	Width [mm]
I	1.63
II	1.21
III	0.77 one-sided
IV	1.44
V	0.7 one-sided
VI	2.12
VII	1.60
VIII	1.01
IX	2.21
X	0.97

The measurement of the flash height give unequivocal image of the joint quality. Lack of homogeneous flash is a result of badly performer process of frontal welding, particularly the selection of parameters.

3.2. Thermovisual research

Thermogram shown in Fig. 16 and the change of temperature in time (Fig. 17) illustrates the diversified thickness of the element, however it does not provide the unequivocal assessment of the joint performed. It results, first of all, from the lack of comparative material, free of flaws.

As it can be observed in Fig. 16 the cause of the problems which appear in the course of joining the tested element is the varied thickness of the wall and the strengthening of the construction with ribbing, which is seen as brighter points. The areas, the ribbing of which is welded are more faulty, which is connected with badly selected parameters of welding process.

Thermal imaging camera however, did not give the required effect, because the thermographic image did not allow the bilateral identification of joint quality.

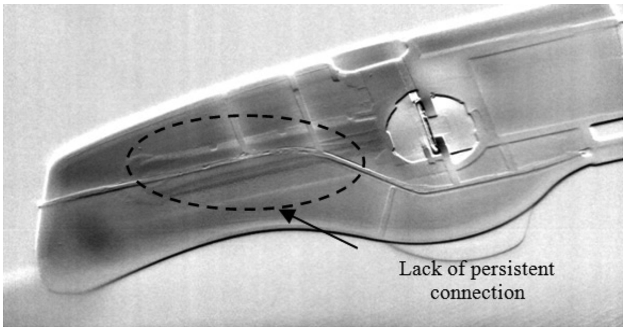


Fig. 16. Thermogram of the sample

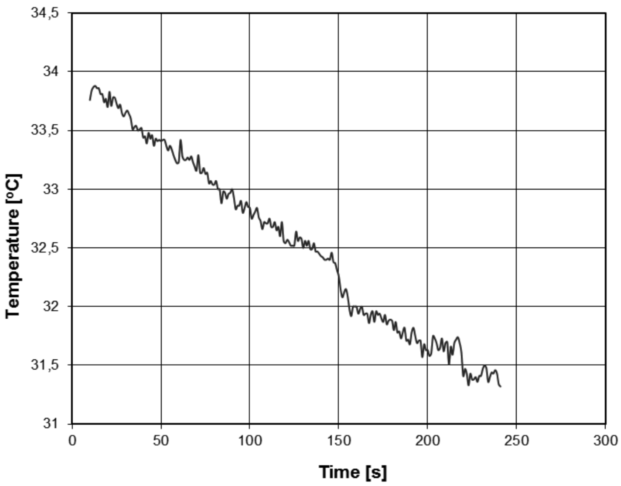


Fig. 17. Diagram of the dependence of temperature on time during the cooling process

3.3. Shearography

The results of the research with the use of shearography method are shown in Fig. 18. It should be stressed that what was subjected to research is an area in which the lowest flash was spotted during the visual testing.

Identified flaw areas were subjected to further analysis with the help of ISISplus program, the results of which are shown in Fig. 19.

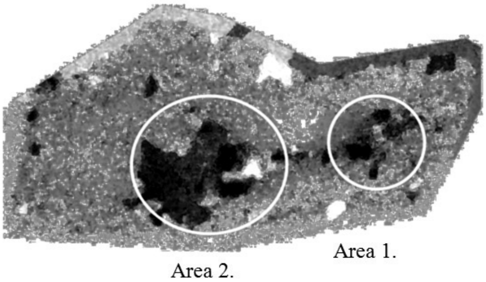


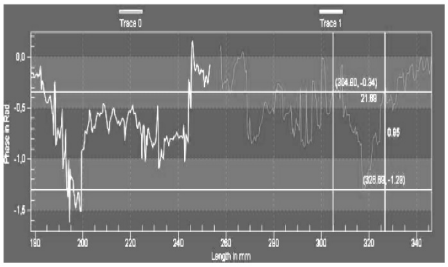
Fig. 18. Identification of joints' flaws with shearography method

The results presented give the possibility of flaw identification, and even determining its size. However, it is still one-sided measurement, which is not satisfying in case of strengthening the element with the ribbing system from inside (the side with no-access, only with the destructive method) and various thickness. Even more then, the visual and thermographic tests provided basis to think that the weld in the areas of ribbing joints is the weakest.

3.4. 3D scanning

The research results, for 10 individual measurement points, conducted by means of spatial scanning with the use of LED lamps is presented in Fig. 20. It is the image ¾ of the circuit of the tested element. Fig. 21. show the area of joint's flaw (a) and the way the deformation was measured.

a)



b)

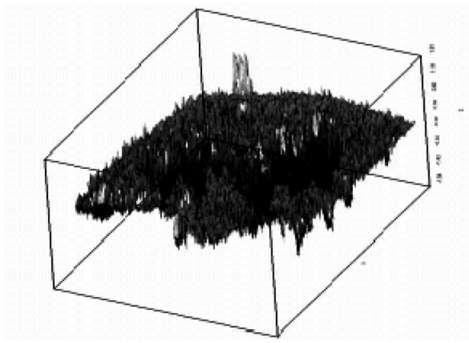


Fig. 19. Exact image of deformation in area 1 - a), 3D view - b)

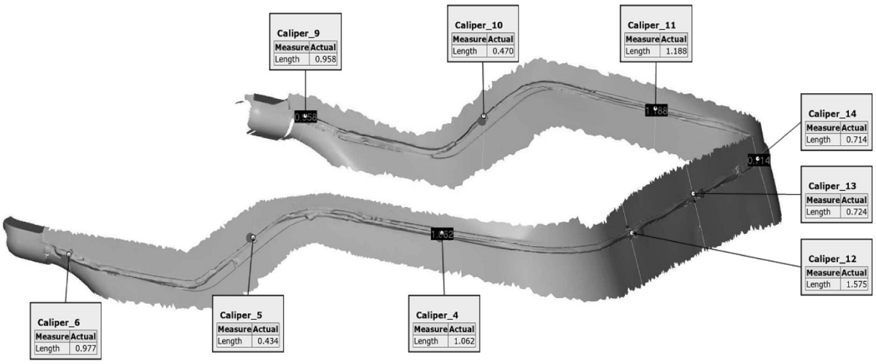


Fig. 20. Measurement of deformations size on the circuit

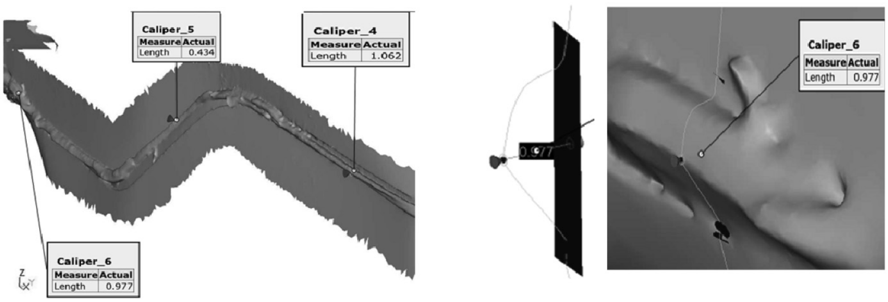


Fig. 21. The area of permanent joint flaw (a) the way of measurement (b)

The image received by means of the spatial scanning method with the use of Comlet L3D provides quick and best visualization of joint quality, which is very important in industrial practice. Exact flash dimensioning enables full quality control.

3.5. Strength tests

Strength testing results are juxtaposed in Table 2, with Fig. 22 show the sample after the tensile test.

As it can be observed, the received properties significantly vary from the catalogue data. The very big scatter of results was observed for values of tensile strength and Young's modulus.

A sample from the measuring point III, despite one-sided flash (only 0.77 mm), has high strength (19.9 MPa) and very high ultimate elongation (386.6%). This fact surprised the authors of this article and it is difficult to explain. Other samples are measured with respect to mechanical properties corresponding to the geometry of the weld.

Table 2.
Strength test results

Measurement point	E [MPa]	σ_M [MPa]	ε_M [%]	σ_B [MPa]	ε_B [%]
I	622	11.9	4.2	2.37	13.5
II	882	30.2	17.7	28.4	18.4
III	608	19.9	18.1	11.0	386.6
IV	712	24.1	11.5	23.5	12.1
V	239	7.2	3.7	1.44	10.3
VI	278	6.1	3.4	1.21	11.1
VII	459	4.77	4.0	0.95	23.7
VIII	453	14.6	5.7	5.26	10.5
IX	537	11.4	6.5	2.29	18.1
X	659	14.5	4.1	2.86	9.2

Fig. 22. Sample after the test

4. Conclusions

On the basis of the research conducted we concluded the following:

1. The tested element was welded by frontal method, but uneven flash proves its flaws, the cause of which are probably badly selected parameters of the process,
2. Out of the presented methods of joint quality assessment, the best result is achieved through 3D scanning, which enables dimensioning of the flaw.
3. The least useful method of verifying the quality of various wall thickness elements seems to be thermovision, as it only enables flaw location.
4. In order to conduct exact analysis all the test performer should be referred to comparative samples which are property welded with the use of the discussed method.

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