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Krzysztof KUCHTA[1]
Rafał SILEZIN[2]
Paweł ŻWIREK[3]

EXECUTION AND INSPECTION OF STEEL HOLLOW SECTIONS WELDED JOINTS

The hollow section welded joints require a number of actions before starting welding and appropriate supervision during this operation to achieve joints with adequate quality level, which should be confirmed by the post-completion tests. The execution of hollow section joints is associated not only with welding, but also with cutting and additional machining of edges. In some cases, weld surfacing is also applied to correct sections fit-up. Weld surfacing and thermal cutting can cause local hardening of connected elements. The welding has to be preceded by an assessment of the previous technological processes. The welded joints can be only executed on the basis of detailed Welding Procedure Specifications (WPS). It is advisable to manufacture – in accordance with previously prepared WPS – pre-production joints for testing, proving the ability of the welding personnel to execute welded joints with specified quality, using the available equipment. The quality of welded joints is proved by testing. A type of conducted tests, thus scope and type of welding defects possible to detect, depends on the weld type, wall thickness of connected elements and joint geometry. The authors' experience indicates that the proper execution of the welded joint of hollow sections is difficult task, which often requires pre-production quality testing of the joints.

Keywords: steel structures, lattice structures, hollow sections, welded joints, welds

1. Introduction

Steel structures of modern buildings or civil engineering works are treated as construction products individually manufactured or custom-made in a non-series process in response to a specific order and installed in a single identified construction work. In this situation, the manufacturer shall provide a declaration of conformity with structure design documentation and PN-EN 1090-2 [4] for steel structure or PN-EN 1090-3 [5] for aluminum structure. In compliance with

[1] Krzysztof Kuchta, Cracow University of Technology, Chair of Metal Structures
[2] Rafał Silezin, NDT SERWIS, ul. Niska 12, 31-306 Kraków, biuro@ndtserwis.pl
[3] Corresponding author: Paweł Żwirek, Cracow University of Technology, Chair of Metal Structures, ul. Warszawska 24, 31-155 Kraków, +48 12 6282033, pzwi@op.pl

the building regulations, metal structures designed according to the Eurocodes have to be executed by the manufacturers who hold Certificate of Factory Production Control according to PN-EN 1090-1 [3]. Execution of a steel structure with parameters assumed in the structural design documentation requires the contractor to take a series of actions - both prior the production process and control activities on the subsequent stages of the execution, to verify the quality of the executed work. Selected issues related to the execution and quality control of welded joints in steel hollow sections are discussed in this paper.

2. Preparation for welding

Steel hollow sections welded joints have to satisfy the requirements of PN-EN 1090-2 [4] concerning the execution of steel structures, necessary to ensure their adequate bearing capacity, stability, serviceability and durability. The contractor should have the necessary qualifications and use appropriate equipment and measures to achieve compliance with the requirements given in the technical specification and in PN-EN 1090-2 [4].

During the execution of welded joints in circular or rectangular hollow sections appropriate guidelines should be used which include provisions about the preparation of joint faces for welding, weather protection, preassembly for welding, welding processes, drawing of the joint, welding sequence, welding position, welding parameters (e.g. welding current, arc voltage, gas flow), heat treatment conditions, etc. To execute welded joint in hollow sections some additional information is required: start and stop positions of each weld (Fig. 1b, 2b) and – if this is the case – the manner and location on the connected section perimeter where the weld passes from fillet into the butt one. Above mentioned information should be included in Welding Procedure Specification (WPS), prepared in accordance with PN-EN ISO 15609-1 [7].

Before the execution of steel structure, the contractor shall ensure that it is able to make a joint with the parameters described in the structural design documentation. One of the elements of the system that enables to obtain welded joints with the required quality is Welding Procedure Qualification Report (WPQR). The aim of the WPQR is to confirm an ability of the steel workshop to execute a particular joint type, with a given geometry and for specify material type, using welding technique available in the workshop. The WPQR is the basis for elaboration of the WPS. Scope of tests related to welding technique qualification depends on execution class, type of parent material and welding technique. In practice, the qualification of welding technique is most commonly carried out on the basis of PN-EN ISO 15614-1 [8], which enables to qualify welding technique for execution classes EXC2, EXC3 and EXC4. Qualification of the welding technique according to PN-EN ISO 15614-1 [8] includes following stages:

– a detailed analysis of the welding production (determination of the basic variables: type of welding process, parent material group, dimensions of the elements, type of the joint – thickness, diameter, welding positions),
– choosing of joint for tests,
– elaboration of the preliminary Welding Procedure Specification (pWPS),
– execution of test specimen,
– destructive and non-destructive testing for welding techniques,
– issuance of the Welding Procedure Qualification Record (WPQR) by the notified body,
– elaboration of the Welding Procedure Specification (WPS).

If the impact testing is required, tests should be carried out at the lowest temperature at which this property has to be obtained according to appropriate Standard for grade of steel used in tests. In the case of steels manufactured according to PN-EN 10025-6 [2], microscopic test of one specimen is necessary, the picture covering the heat affected zone (HAZ), melting zone, and a filler material zone has to be taken. For elements with temporary corrosion coating, test should be performed by joining the elements with the largest acceptable thickness equal to the nominal coat thickness plus the value of tolerance.

3. Profiles preparation and execution of welding

Frequently in their engineering practice, the authors had to deal with documentation in which the issue of welded joint in hollow sections was treated in an imprecise way. In the design documentations, the designers very often put the graphical symbol of the circumferential weld to describe joint on the drawing. There are also structural design documentations where the weld thickness is given only in the form of description with relation to element thickness.

Structures designed according to Eurocode 3 [6] should be executed in accordance with the Standard PN-EN 1090-2 [4] – which, in the case of welded joints in hollow sections, refers to PN-EN ISO 9692-1 [14]. Each of these Standards give different ranges of butt weld application, which may cause that, from a technological point of view, type of weld assumed by the designer is impossible to execute. This issue will be further developed by the authors. For welded joint in rectangular hollow sections PN-EN 1090-2 [4] describes how to prepare profiles for welding for two variants: butt welds (Fig. 1c) and fillet welds (Fig. 1d). Preparation of faces in hollow section joint for the one-side welding should met the provisions of PN EN ISO 9692-1 [14] and PN EN ISO 9692-2 [15].

According to the information given in Figures 1 and 2, both for circular and rectangular hollow sections the same weld type around the whole perimeter can be obtained only if the angle θ ranges from 60° to 90°.

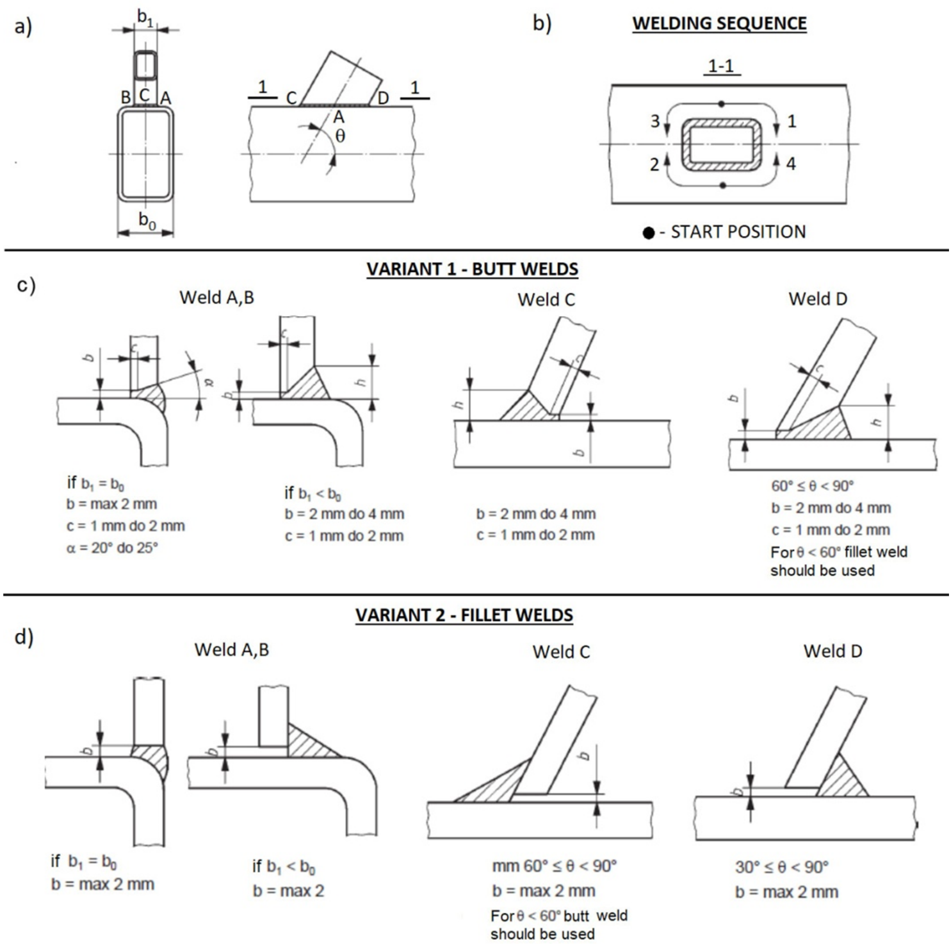

Fig. 1. Welded joints in rectangular steel hollow sections: a) description of welds and dimensions, b) start and stop positions and welding sequence, c) preparation of joint faces in the case of butt welds, d) preparation of joint faces in the case of fillet welds

When the angle θ is lower than 60^o the weld D (see Fig. 1a, 2a) should be executed as fillet weld, while the weld C – as butt weld. It causes that on the perimeter of the connected sections exist two types of welds – butt and fillet. According to PN-EN 1090-2 [4], welding of branch connections in hollow section with the angle θ lower than 60^o should be qualified on the basis of special tests.

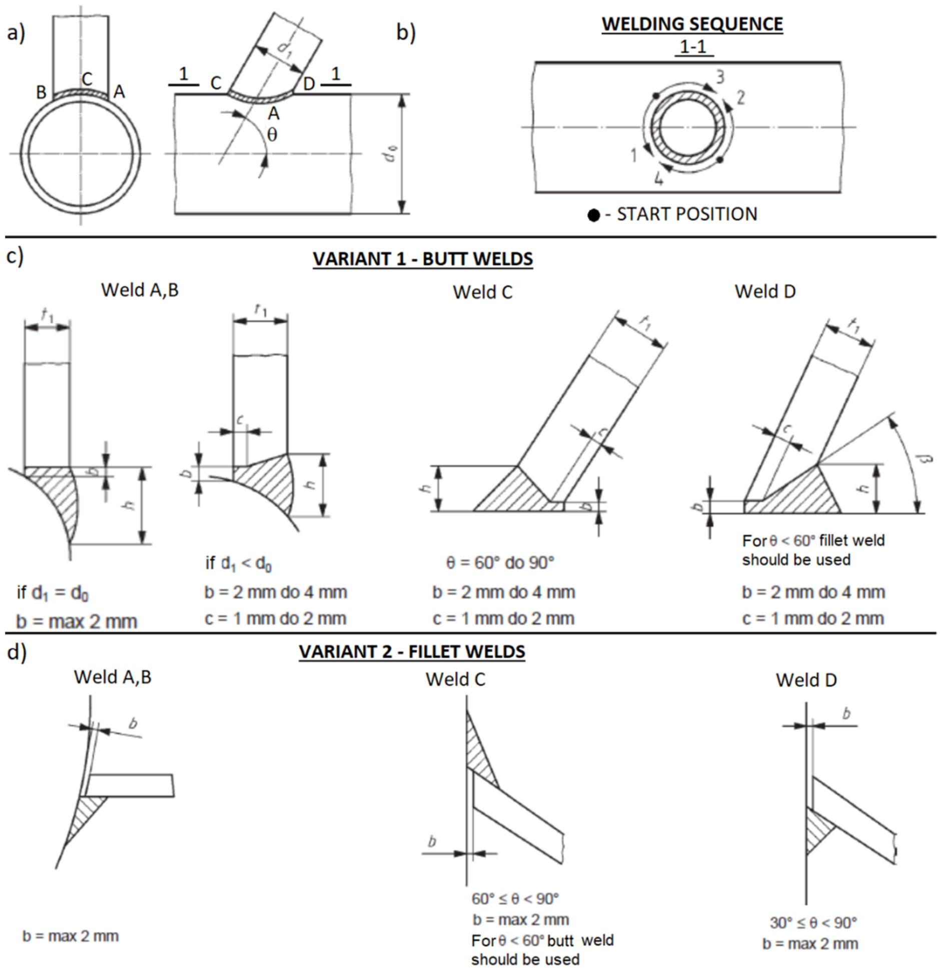

Fig. 2. Welded joints in circular steel hollow sections: a) description of welds and dimensions, b) start and stop positions and welding sequence, c) preparation of joint faces in the case of butt welds, d) preparation of joint faces in the case of fillet welds

It may be noticed that Fig. 1 and 2 give some recommendations that are worth to be taken into account during detailing the lattice structures made of rectangular hollow sections. While in the case of fillet welds it is permitted that brace fully adjoin chord, in the case of butt welds the appropriate gap between the connected elements should be ensured. This gap can be obtained by introducing in the workshop documentation appropriately shorter elements which reduces the labour consumption of the preparatory work, and thus decreases the cost of structure execution. For example, for the angle of inclination θ=60^{o}, the element should be 4.6–9.2 mm shorter, what is much greater value than length tolerances according to PN-EN 1090-2 [4]. For circular hollow sections standard PN-EN 1090-2 [4] does not indicate the position where welds A and B should transform from fillet to butt one. The authors propose assuming that it take place at the point where the angle between generatrix of brace external shell and tangent to the chord is equal to 120°.

In the case of joints of lattice structures made of rectangular hollow sections, elements are usually cut by band saw. This process that does not change the hardness of the material and therefore do not increase the risk of cracking after welding. If thermal cutting processes (e.g. laser cutting, plasma cutting) are used, their capability should be periodically checked because of their influence on steel mechanical properties, particularly hardness. The verification consists in taking of four samples from the constituent product to be cut by the process [4]:

1. a straight cut from the thickest constituent product,
2. a straight cut from the thinnest constituent product,
3. a sharp corner from a representative thickness,
4. a curved arc from a representative thickness.

The quality of cut surfaces is defined according to PN-EN ISO 9013 [12] and should fulfil provisions given in Table 9 of PN-EN 1090-2 [4]. If hardness test is required, the results should be in accordance with Table 10 of PN-EN 1090-2 [4]. In this case, capability of the processes that may cause local changes of steel hardness (thermal cutting, shearing, punching) should be checked. In order to achieve the required hardness of free edge surfaces, preheating of material may be applied. The check of the process capability is carried out as follows: four samples are taken from the structural products that are most susceptible to local hardening, four local hardness tests are done on each sample according to PN-EN ISO 6507 [11], in locations likely to be hardened. This allows to confirm the lack of influence of cutting method on steel weldability.

For joints in rectangular hollow sections with fillet welds, when the chord and brace profiles have the same width (see Fig. 1, weld A and B, the case $b_1=b_0$), and the chord has a large fillet radius, the adjustments to the width of the excessive gap between the connected parts may be needed (see Fig. 3).

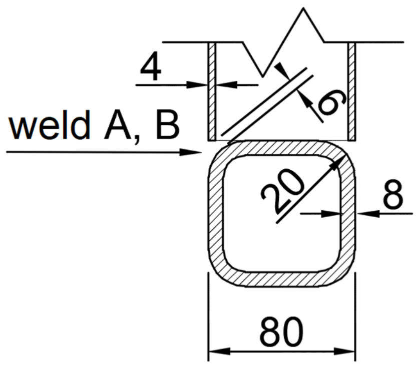

Fig. 3. Exemplary geometry of the brace to chord joint with the same section width

In this case, preparation for welding should include additional grinding of raw cut surface after cutting by band saw. However, to make this solution possible – the workshop drawings should include the appropriate length overmeasure. An alternative solution is brace weld surfacing [1]. This process should be carried out as a single-pass and, similarly as thermal cutting or welding, requires appropriate WPS. If there is a need to correct the lack of fitting of connected elements, the weld surfacing can also be used, even if braces have lower width b_1 than chord b_0 (Fig. 1a). In the case of joints in circular hollow sections, it is most convenient to shape element ends using computer-controlled plasma or laser cutting machine. This technology provides almost ideal surface of the groove weld edges. It is also possible to shape the groove weld edges with the use of oxyfuel gas cutting but, in this case, a significantly lower quality of surface of groove weld edges is obtained. Possibility of increased hardness of the cut surface also has to be taken into account.

Welded joints in hollow sections are executed using the following processes according to PN-EN ISO 4063 [9]:
– 111: manual metal arc welding (metal-arc welding with covered electrode),
– 135: metal active gas welding (MAG welding),
– 136: tubular-cored metal arc welding with active gas shield.

The welding methods 135 or 136 cannot be in practice applied for the execution of parts of the weld D if the angle θ is lower than 50° due to the lack of appropriate access for the welding nozzle to achieve proper weld penetration. In this situation, the welding in this zone have to be carried out using the covered electrode 111 method; and the remaining part of perimeter by 135 or 136 methods. The start and stop positions (see Fig. 1b, 2b) of welds for hollow sections in the lattice structures should be given in Welding Procedure Specifications. Branch connections in hollow sections of lattice structures, containing combined welded joints (with filled and butt welds), can be welded without backings. Flat grinding of one-sided butt welds welded without backings is not permissible. This type of welds may be flat grinded to the level of parent material surface, only if they were entirely welded with backings.

4. Testing of welded joints in hollow sections

The issues described in the previous paragraph cause that the execution of the welded joints in hollow sections with appropriate quality is, as practice shows, quite difficult. This follows from the fact that on section perimeter butt and fillet welds may exist alternately. Moreover, due to the geometrical limitations, the use of different welding methods (111 and 135 methods) may be needed. In addition, it may be necessary to correct the fit-up of connected elements by weld surfacing. For example, for braces leaned at an angle of 45° the weld D should be executed by 111 method, which requires, after formation of each beads, proper cleaning and grinding of weld start and stop positions. Furthermore, the weld D must be finished outside the corner, as shown in Fig. 1b. As a result, at the point where the welding method is changed from 111 to 135, the type of the weld also changes from fillet to butt. This requires of welders using many different Welding Procedure Specifications.

Quality levels for imperfections in welded joints are given in PN-EN ISO 5817 [10], but the imperfections related to weld shape and micro crack fusion are not considered. The quality levels are associated with element or structure execution class EXC. For the execution class EXC1, quality level D is assumed. Execution class EXC2 is usually associated with quality level C or level D for undercuts, overlaps, stray arc and warm-holes. Execution class EXC3 corresponds to quality level B, while EXC4 to level B+ i.e. quality level B with additional requirements. It should be stressed that according to the Design Standard PN-EN 1993-1-8 [6] quality level C is usually required for steel joints. The scope of nondestructive testing (NT) methods is determined depending on the structure execution class, type and location of welds, and resistance utilization factor. For this reason, the designer should indicate in the workshop documentation if the resistance utilization factor for transversely tensioned butt welds is lower or equal to 50% or if this value is exceeded. In the case of fillet welds the information about resistance utilization factor is not required.

Fig. 4. Position of magnetic defectoscope during ultrasonic testing (UT) of brace to lower chord assembly splice

If there is a need to verify assumed quality level for certain geometry of joints (angle $\theta < \sim 30^o$) with complete-penetration butt welds, it is not possible to use non-destructive methods, i.e. radiographic testing (RT) or ultrasonic testing (UT). In this case only magnetic particle testing (MT) or penetrant testing (PT) can be conducted – but these tests allow to detect only surface imperfections. Radiographic testing is usually not applied in the case of hollow sections. Ultrasonic testing which reveal both surface and interior of the weld, such as: cracks, lack of fusion or delaminations, can be applied only in the case of butt welds and sections with the width higher or equal to 8 mm. Ultrasonic testing is exceptionally allowed for section thickness of at least 6 mm. In this situation research program approved by the welding personnel with the third, the highest degree of qualification is required. Ultrasonic testing for weld C (Fig. 1a, 2a) may be difficult or impossible in the case of the joints where more than one brace is connected to the chord due to a need for using a magnet yoke (see Fig. 4).

The MT and PT method may be used for all types and locations of the welds, but it should be pointed out that these methods reveal only surface defects. In the case of fillet welds, using the UT is impossible.

Regardless of the test types listed in Table 1, all welds should be visually examined on entire length.

Table 1. Scope of available non-destructive testing (NDT) depending on weld type and its location on section perimeter

	Weld location according to Fig. 1 and 2		
Type of tested weld	A, B	C	D
Butt weld	UT MT, PT	UT MT, PT	UT (θ>30^o) MT, PT
Fillet weld	MT, PT	MT, PT	MT, PT

During the examination of weld shape and surface of the branch connections in hollow sections, particular attention shall be paid to the following areas on section perimeter:

1. extreme front and rear positions, and two side positions in circular hollow section joints,
2. four corners in rectangular hollow section joints.

This means that the geometry and the type of welds indicated in the documentation affects the possibility of detecting weld imperfections. For this reason it is extremely important to manufacture so-called pre-production joints to check ability of the welders to execute this type of welded joints. The joint should be examined macroscopically, its imperfections should be indicated, and welding technique enabling to avoid possible future imperfection should be evaluated. Qualification testing of welders shall be carried out in accordance with PN-EN ISO 9606-1 [13]. In the case of hollow sections joints with element inclination angles lower than 60° qualification of welds shall be carried out on the basis of special tests - as defined in PN-EN 1993-1-8 [6].

Figure 5 shows the most common imperfections, detected during tests of pre-production joints in hollow sections. The lack of fusion is demonstrated in following figures: Fig. 5a (on the internal surface of the brace), Fig. 5b (between beads in the weld C) and Fig. 5d (in the weld D). Figure 5c presents improper penetration in the weld D. The authors' experience indicates that, in practice, the weld D requires the longest preproduction preparations in order to obtain properly executed welds at a given quality level. The above imperfections result from problems with appropriate access for the welding nozzle to the place of welds execution or with necessity of welding using 111 method.

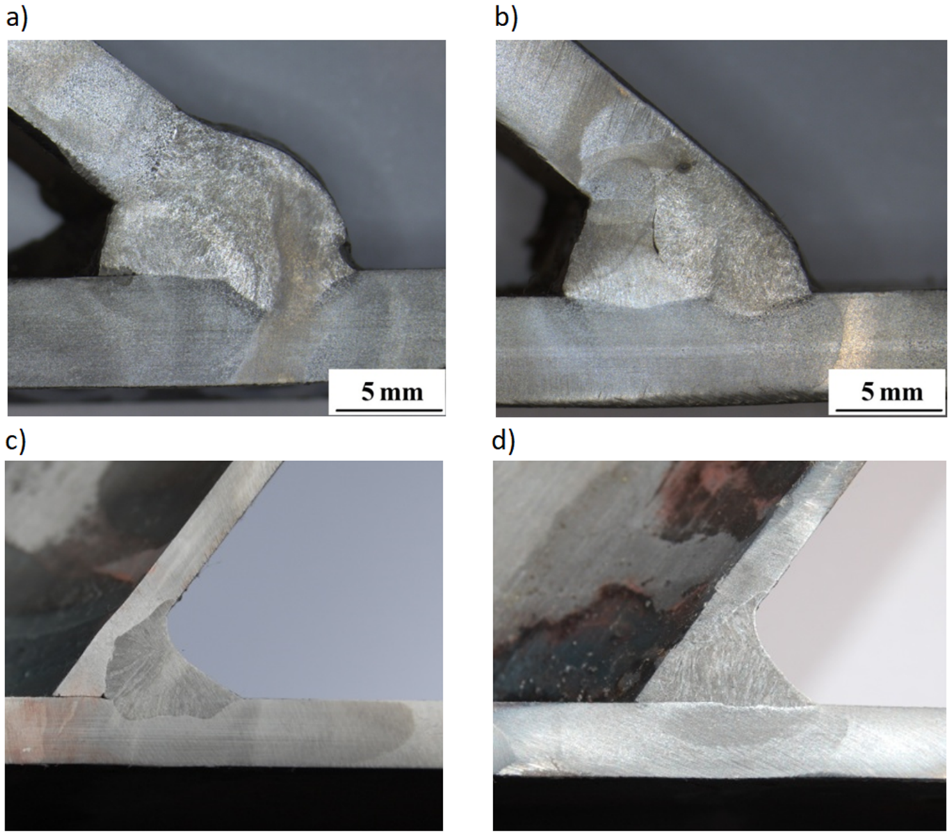

Fig. 5. Welding imperfections detected in the pre-production joints. Description in the text

5. Summary

The execution of welded joints in hollow sections, apart from welding works, may include cutting (also thermal cutting), additional machining of sections edges, and in some cases – weld surfacing to correct elements fit-up. As the practice shows, the execution of this joint type at appropriate quality level is the difficult issue because in some joint geometrical configurations on the same section perimeter both fillet and butt welds have to be executed. In addition, due to the geometrical limitations, it may be necessary to use different welding techniques (111 method and 135 or 136 method). In some cases prior correction of section fit-up by weld surfacing of selected walls may be needed. These circumstances illustrate the importance of pre-production assessment to be sure that given manufacturer, using the specified equipment and personnel, is able to execute welded joints at the appropriate and consistent with design documentation quality level. Joint shape and weld type indicate possible types of quality control tests. Volumetric test methods, revealing weld internal imperfections can be used only in the case of butt welds and sections with wall thickness not smaller than 8 mm (exceptionally 6 mm). In all other cases magnetic particle (MT) or penetrant (PT) testing, detecting only surface imperfections, can be used. This shows the necessity of manufacturing and testing the pre-production joints, which can be utilized to confirm that the measures used together with the welders skills enable execution of welded joints at the appropriate quality level.

References

[1] Klimpel A., Napawanie i natryskiwanie cieplne, Wydawnictwo Naukowo-Techniczne, Warszawa 2000.

[2] PN-EN 10025-6 Hot rolled products of structural steels. Technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition.

[3] PN-EN 1090-1 Execution of steel structures and aluminium structures. Part 1 – Requirements for conformity assessment of structural components.

[4] PN-EN 1090-2 Execution of steel structures and aluminium structures. Part 2 – Technical requirements for steel structures.

[5] PN-EN 1090-3 Execution of steel structures and aluminium structures. Part 3 – Technical requirements for aluminium structures.

[6] PN-EN 1993-1-8 Eurocode 3. Design of steel structures. Design of joints.

[7] PN-EN ISO 15609-1 Specification and qualification of welding procedures for metallic materials. Welding procedure specification. Arc welding.

[8] PN-EN ISO 15614-1 Specification and qualification of welding procedures for metallic materials. Welding procedure test. Arc and gas welding of steels and arc welding of nickel and nickel alloys.

[9] PN-EN ISO 4063 Welding and allied processes. Nomenclature of processes and reference numbers.

[10] PN-EN ISO 5817 Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections.

[11] PN-EN ISO 6507 Metallic materials. Vickers hardness test.

[12] PN-EN ISO 9013 Thermal cutting. Classification of thermal cuts. Geometrical product specification and quality tolerances.

[13] PN-EN ISO 9606-1 Qualification testing of welders. Fusion welding. Steels.
[14] PN-EN ISO 9692-1 Welding and allied processes. Types of joint preparation. Manual metal arc welding, gas-shielded metal arc welding, gas welding, TIG welding and beam welding of steels.
[15] PN-EN ISO 9692-2 Welding and allied processes. Joint preparation. Submerged arc welding of steels.

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