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*Original scientific paper*

# MECHANICAL TESTING OF HLAW WELDED JOINTS IN ACCORDANCE WITH EUROPEAN STANDARDS – THEORETICAL APPROACH

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A b s t r a c t: Hybrid laser arc welding is a relatively new welding process, whereby combining the advantages of two different processes, laser beam welding and gas metal arc welding, represents an excellent substitute for conventional welding processes, but has not yet been sufficiently elaborated and researched. Additional research should be carried out in terms of hybrid welding technologies, this leads to the creation and development of new standards and procedures that would confirm their validity. The mechanical tests that could be destructive and non-destructive are the primary indicator of the quality of the welded joint and the qualification of the welding technology. This paper presents the current procedure for mechanical testing of welded joints performed by hybrid laser arc welding and the design of the test specimens that depends on the type of the testing method and conditions in the relevant application standard. In the final part, general conclusions are drawn regarding the standards covering the welded joint quality performed by hybrid laser welding.

**Key words:** hybrid welding; test specimens; mechanical testing; standard; procedure

## МЕХАНИЧКО ИСПИТУВАЊЕ НА ЗАВАРЕНИ СПОЕВИ ИЗВЕДЕНИ СО ХИБРИДНО ЗАВАРУВАЊЕ СОГЛАСНО СО ЕВРОПСКИТЕ СТАНДАРДИ – ТЕОРЕТСКИ ПРИСТАП

А п с т р а к т: Хибридно заварување со ласерски зрак и електричен лак е релативно нов процес на заварување кој преку комбинирање на предностите на два различни процеса, заварување со ласерски зрак и полуавтоматско заварување со топлива електродна жица под заштитен гас, претставува одлична замена за конвенционалните процеси на заварување, но сè уште не е доволно елаборирaн и истражен. Треба да се изведат дополнителни истражувања поврзани со технологиите за хибридно заварување, што доведува до создавање и развој на нови стандарди и процедури кои би ја потврдиле нивната валидност. Механичките испитувања се основен показател со кој се определува квалитетот на заварениот спој и квалификација на технологијата на заварување и тие испитувања можат да се изведат со разорување и без разорување. Овој труд ја елаборира тековната постапка за механичко испитување на заварени спoеви изведени со хибридно заварување со ласерски зрак и електричен лак, како и дизајнот на епруветите кој зависи од видот на испитувањето и условите на примена. Накрај се изведени генерални заклучоци во однос на стандардите кои го покриваат квалитетот на заварениот спој изведен со хибридно заварување со ласерски зрак и електричен лак.

**Клучни зборови:** хибридно заварување; епрувети; механичко испитување; стандарди; процедури

## 1. INTRODUCTION

Today's globalization is characterized by an accelerated process movement of capital, resources, products and services, resulting in a completely new world trade structure, economic and financial flows, internationalization of production, and acceleration of technical and technological development. As a part of mechanical engineering, the welding have not been lagging in technological development, new welding techniques and technologies are constantly being introduced, which would result in reduced production costs and improved technical characteristics of the welded joints [1].

Hybrid laser arc welding (HLAW) is a relatively new welding process, whereby combining the advantages of two different processes: laser beam welding – LBW, and semi-automatic welding processes such as gas metal arc welding – GMAW, and flux-cored arc welding – FCAW, represents an excellent substitute for conventional welding processes [2, 7].

The implementation of new welding techniques and technologies leads to the creation and development of new standards and procedures that would confirm their validity.

Mechanical tests are a primary indicator that determines the mechanical properties of welded joins, and they can be done destructively or non-destructively. The tests give results that, if within predetermined needs and criteria, guarantee the safety of the welded structure, but if the results prove to be 'poor', they indicate defects in the welded joint and require corrective actions to meet the required criteria.

The mechanical testing of the welded joints can be performed in two ways, on a fully welded structure or test pieces – test specimens made from a part of the welded structure, and the second way, laboratory test specimens prepared and made under the general conditions of welding in production, which they shall represent.

Depending on the required criteria, the mechanical testing of the welded joint can be performed on:

- Test specimens are entirely made of weld metal (made in molds). The obtained results will define the weld metal's mechanical properties without considering the base material influence;
- Test specimens are made of welded joints where the base material has been melted and with a certain percentage mixed in the molten mixture during the welding process. The percentage of participation of the base material in the weld metal depends on the welding procedure and welding parameters such as the welding current, voltage, diameter of the electrode-welding wire, welding speed, welding position, etc.

In this paper, the current procedure for mechanical testing of welded joints performed by hybrid laser arc welding HLAW is presented. The procedures for the preparation of test specimens for mechanical testing have been elaborated in detail depending on the welded joint as well as the type of mechanical testing (tensile test, bending, toughness test, etc.).

## 2. PRODUCTION OF TEST PIECES – WELDED SPECIMNES

The production of the test pieces – welded specimens, must be carried out in accordance with the prescribed norms and standards for the welding procedure as well as the type of material which is welded, while taking care that they are fully prepared and made under conditions that correspond to the production or assembly of the welded structure.

In order to determine the quality of the welded specimens and their mechanical properties and thus qualify the welding technology, it is necessary to carry out destructive and non-destructive testing after the welding process. The following types of tests are mainly performed to determine the quality of the welded specimens:

- Non-destructive testing of welded specimens:
  - Visual and dimensional control.
  - Liquid penetrant testing.
  - Magnetic particle testing.
  - Ultrasonic inspection.
  - Radiographic inspection.
- Destructive (mechanical) testing of welded specimens:
  - Tensile test.
  - Bend test.
  - Impact testing.
  - Hardness testing.
  - Metallographic inspection of the weld and HAZ.

The testing procedures for welded specimens performed by hybrid laser arc welding – HLAW, must be performed in accordance with the standard EN ISO 15614-1, more precisely with standard EN ISO 15614-14 – Specification and qualification of welding procedures for metallic materials – Welding procedure test – Part 14: Laser-arc hybrid welding of steel, nickel and nickel alloys [3, 4].

This standard proves the validity of the welding technology of the test piece and a welding procedure qualification record (WPQR) is issued based on it. For the purpose of complete inspection, the test piece should have sufficient size to ensure good heat distribution and sufficient surface area to be able to produce all the required test specimens. The rolling direction should also be marked on the welded specimen for caution when the test specimens are produced from the heat-affected zone [3].

In addition, the operator of the welding equipment should be certified according to the standard EN ISO 14732, while the welding parameters should be in accordance with the preliminary welding procedure specification – pWPS [5, 6].

The dimensions and shape of the welded specimens depend on the type of the weld, for a butt weld the following dimensions are required (Figure 1):

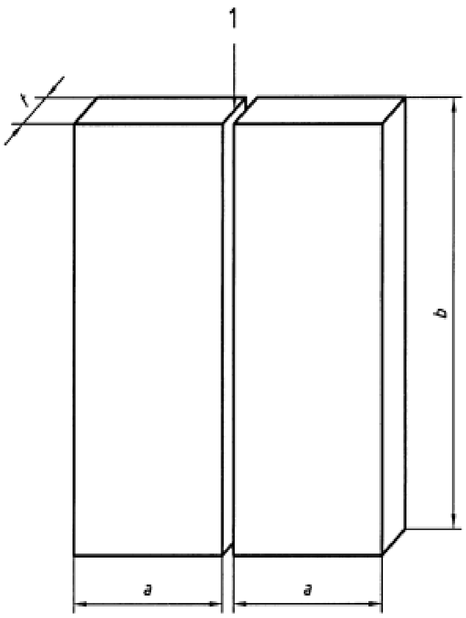



**Fig. 1.** Dimensions of a test piece for a butt joint in plate with partial or full penetration [4]

1 – Preparation of the groove and positioning in accordance with pWPS; *t* – material thickness; *a* – minimum 150 mm; *b* – minimum 350 mm

## 3. EXAMINATION AND TESTING OF TEST PIECES – WELDED SPECIMENS

Welded specimens after the welding process are tested with destructive and non-destructive tests in order to determined the quality of the welded joint. Depending on the type of weld, the test pieces should be in accordance with Table 1.

### 3.1. *Location and taking of test specimens*

Before being cut out of the test piece, test specimens should be marked into several locations depending on how many and what types of test specimens are needed to test the mechanical characteristics of the welded joint.

The test specimens shall be cut out, wherever possible by a mechanical process, and machined to the required dimensions. If the test specimens are cut from the test piece by a thermal process, they must be wide enough to ensure that the heat-affected zone can be completely machined off.

T a b l e 1

*Examination and testing of the test pieces [4]*

| Test piece | Type of test | Extent of testing | Footnote |
|---|---|---|---|
| Butt joint with full penetration | Visual | 100 % | – |
| | Radiographic or ultrasonic | 100 % | a |
| | Surface crack detection | 100 % | b |
| | Transverse tensile test | 2 specimens | – |
| | Transverse bend test | 4 specimens | c |
| | Impact test | 2 sets | d |
| | Hardness test | Required | e |
| | Macroscopic examination | 1 specimen | – |
| T-joint with full penetration | Visual | 100 % | f |
| Branch connection with full penetration | Surface crack detection | 100 % | b and f |
| | Ultrasonic or radiographic | 100 % | a, f and g |
| | Hardness test | Required | e and f |
| | Macroscopic examination | 2 specimens | f |
| Fillet welds | Visual | 100 % | f |
| | Surface crack detection | 100 % | b and f |
| | Hardness test | Required | e and f |
| | Macroscopic examination | 2 specimens | f |

[a] Ultrasonic testing shall not be used for $t < 8$ mm and not for material groups 8, 10, 41 to 48.

[b] Penetration testing or magnetic particle testing. For non-magnetic materials, penetration testing.

[c] For bend tests, see 7.4.3.

[d] 1 set in the weld metal and 1 set in the HAZ for materials ≥ 12 mm thick and having specified impact properties. Application standards may require impact testing below 12 mm thick. The testing temperature shall be chosen by the manufacturer with regard to the application or application standard but not be lower the parent metal specification. For additional test see 7.4.5.

[e] Not required for parent metals: sub-group 1.1. and groups 8, 41 to 48.

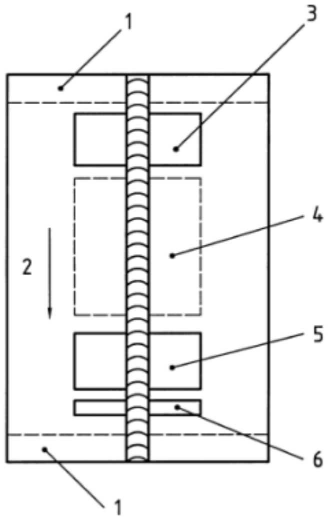
[f] Tests as detailed do not provide information on the mechanical properties of the joint. Where these properties are relevant to the application an additional qualification shall also be held, e.g. a butt weld qualification.

[g] For outside diameter ≤ 50 mm no ultrasonic test is required.

[F] For outside diameter > 50 mm and where it is not technically possible to carry out ultrasonic examination, a radiographic examination shall be carried out provided that the joint configuration will allow meaningful results.

The test specimens for mechanical testing should be taken after all non-destructive testing has been carried out and which has passed the relevant inspection criteria. If the test piece has imperfections within the acceptable tolerance for non-destructive testing, it is acceptable to take the test specimens from locations not provided within the standard.

The location for the test specimens depends on the type of the weld, for a butt weld it should be in accordance with Figure 2.




1. Discard 25 mm.
2. Welding direction.
3. Area for:
   – 1 tensile test specimen,
   – bend test specimens.
4 Area for:
   – impact and additional test specimens if required.
5. Area for:
   – 1 tensile test specimen
   – bend test specimens.
6. Area for:
   – 1 macro test specimen;
   – 1 hardness test specimen.

**Fig. 2.** Location of test specimens for a butt joint in plate [4]

### 3.2. *Tensile tests*

The tensile test is the most widely applied static test that provides a lot of information on the mechanical characteristics of the material under test. The tensile test is carried out to determine the tensile strength (Rm), breaking strength, contraction and elongation, yield strength (ReH), young's modulus and proportional limit stress [9].

The basic principle in the design of the welded structures is that the weld strength should be equal or higher than the base material strength. The test specimen must be made of the same material as the structure, while separating the test specimens from the base material, care should be taken for structural changes that would affect the final test results.

Tensile test specimens can be technical or standardized. The technical test specimens are tested in the state of application of the product, without special machining of the measurement length. On the other hand, the standard tensile test specimens should be made in accordance with standard EN ISO 4136, and they can have a cylindrical or prismatic cross-section [8].

The standard allows the test specimens to be taken from locations with minimum imperfections acceptable in non-destructive testing.

The symbols and abbreviated terms to be used for the tensile test specimens are specified in Table 2 and represented in Figure 3.

The test specimen should be taken transversely from the welded joint, which after machining, the weld axis should be in the middle of the parallel length (Lc) of the test specimen [8].

Additional heat treatment shall not be applied to the welded joint or to the test specimen unless previously specified, in case of heat treatment, any details shall be recorded in the test report. If the test specimens are cut from the welded plate with a thermal process, cuts should be made at a minimum distance of 8 mm from the surfaces of the final parallel length (Lc) of the test specimen [8].

T a b l e 2

*Symbols and abbreviated terms for tensile test specimens [8]*

| Symbol | Terms | Unit |
|---|---|---|
| b | Width of the parallel length | mm |
| $b_1$ | Width of shoulder | mm |
| d | Diameter of the plug | mm |
| D | Outside diameter of the pipe | mm |
| $L_C$ | Parallel length | mm |
| $L_O$ | Original gauge length | mm |
| $L_S$ | Maximum width of the weld after machining | mm |
| $L_t$ | Total length of the test specimen | mm |
| r | Radius of shoulder | mm |
| t | Thickness of the welded joint | |
| $t_s$ | Thickness of the test specimen | mm |

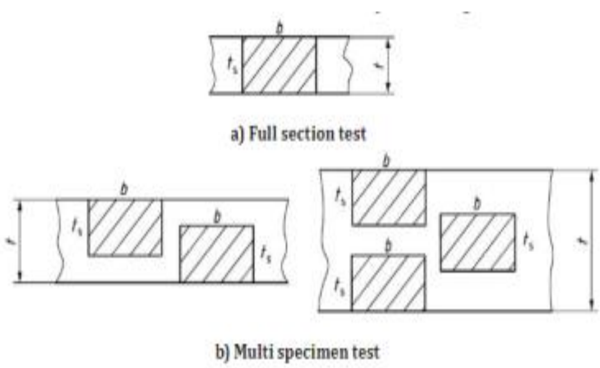



**Fig. 3.** Location of test specimens depending on the thickness of the welded joint [8]

In general, the thickness of the tensile test specimen ($t_s$), should be equal with the base material thickness near the welded joint (Figure 3a). If the base material has thickness >30 mm and the application requires testing of full thickness, several test specimens should be produced from different levels to cover the full thickness of the welded joint (Figure 3b).

The dimensions and shape of the test specimen shall be in accordance with those given in Table 3, with reference to the symbols in Figure 4 and Table 2. The thickness of the test specimen should be constant along the parallel length (Lc) [8].

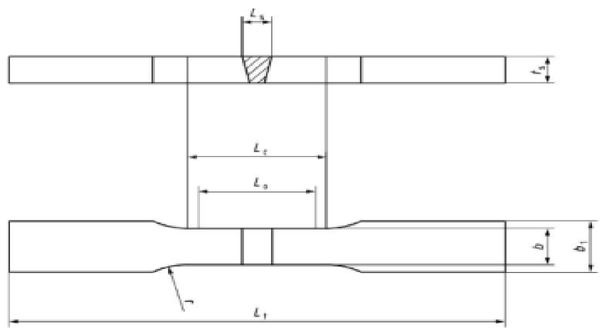


**Fig. 4.** Tensile test specimen for a butt joint in plate [8]

T a b l e 3

*Dimensions of the tensile test specimens for a butt joint [8]*

| Denomination | | Symbol | Dimensions |
|---|---|---|---|
| Total length of the test specimen | | $L_t$ | To suit particular testing machine |
| Width of shoulder | | $b_1$ | b + 12 |
| Width of the parallel legth | plates | b | 12 for $t_s \leq 2$<br>25 for $t_s > 2$ |
| | pipes | b | 6 for D ≤ 50<br>12 for 50 < D ≤ 168,3<br>25 for D > 168,3 |
| Parallel length [a b] | | $L_C$ | $\geq L_s + 60$ |
| Radius at shoulder | | r | ≥ 25 |

## 3.3. *Bend test*

The bend test aims to check the deformation capabilities of the welded joint, and it is a part of technological tests, while the bending strength represents the essential characteristics of resistance to bending. This test should be in accordance with standard ISO 5173.

The standard specifies 9 types of bend test specimens made transversely and longitudinally to the welding direction. Usually, there are made test specimens for transverse root and face bend tests of butt welds, but depending on the base material thickness, lateral test specimens are made for side bend test in such a way that after machining the weld axis will remain in the center of the test specimen [10].

The symbols and abbreviated terms to be used for the bend test specimens are specified in Table 4 and represented in Figures 5 and 6.

T a b l e 4

*Symbols and abbreviated terms for bend test specimens [10]*

| Symbol | Description | Unit |
|---|---|---|
| A | Min. elongation after destruction depending of the material | % |
| b | Test specimen width | mm |
| d | Internal roller diameter (presser) | mm |
| I | Distance between the rollers | mm |
| $L_f$ | Starting distance between the roller contact and the weld axis | mm |
| $L_s$ | Maximum weld width after treatment | mm |
| $L_t$ | Test specimen total length | mm |
| r | Test sample edges radius | mm |
| t | Welded sample thickness | mm |
| Ts | Test specimen thickness | mm |
| α | Bending angle | ° |

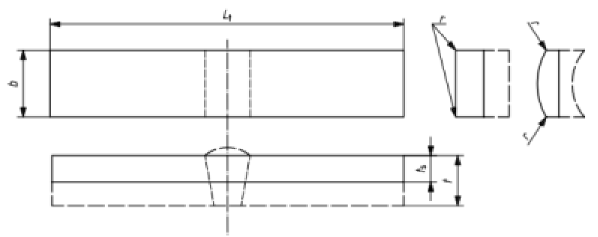


**Fig. 5.** Transverse face bend test specimen for a butt weld [10]

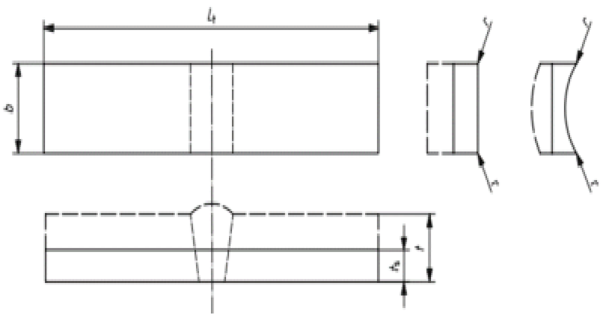


**Fig. 6.** Transverse root bend test specimen for a butt weld [10]

Heat treatment shall not be applied to the welded joint or the test specimen unless previously specified, if a thermal process is used to extract the test specimen from the welded plate, the cuts shall be made at the minimum distance of 3 mm from the test specimen [10].

The test should be carried out by placing the test specimen on two parallel supports, where the weld will be in the middle and is bent by applying force from an upper roller. The bending takes place continuously until a 2 mm crack appears, after which the bending angle is measured. Otherwise, the bending takes place until the test specimen sides are parallel, up to a bending angle of 180º.

In general, the test specimen thickness for transverse root and face bend test ($t_s$), shall be equal to the thickness of the base material near the welded joint (Figure 7a). If the base material thickness is greater than 10 mm, the test specimen thickness shall be machined from one side to a thickness equal to 10 ± 0.5 mm, while the root or face of the weld shall be in tension zone. When the application requires testing of a full thickness >10 mm, several test specimens shall be taken in order to cover the full thickness of the welded joint (Figure 7b). The same procedure shall be for the side bend test.

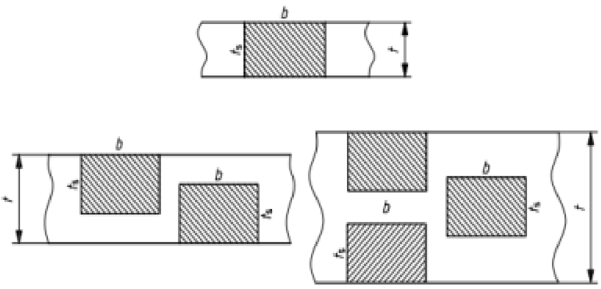


**Fig. 7.** Root and face bend test specimens for a butt weld [10]

In terms of the dimensions, the width (b) of the test specimen for transverse root or face bend test shall be 4$t_s$ or greater, unless otherwise specified in the relevant application standard. The total length ($L_t$) of the test specimens shall be equal to the required value, i.e. from 250 mm to 450 mm for test specimen thickness up to 30 mm, on the other hand, the dimensions are related to the diameter of the upper roller and distance between supports [10, 11].

## 3.4. *Impact test*

The purpose of this test is to determine the toughness of the weld and HAZ, therefore the test specimen with V or U-notch shall be used, according to standard ISO 9016 (Figure 8).

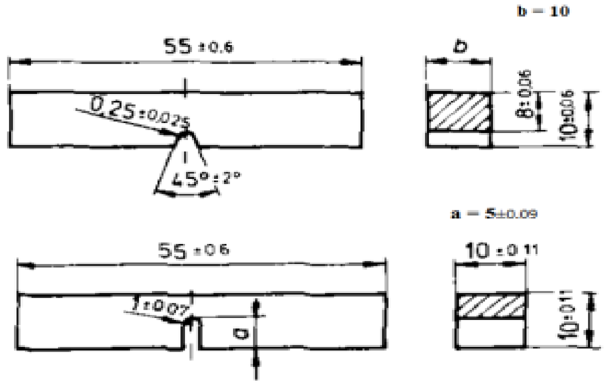



**Fig. 8.** Impact test specimens with V or U notch [12]

The Charpy impact test is performed on a Charpy pendulum, which should be constructed and installed according to standard EN 10045-2.

The test shell be carried out at the specified temperature, usually 23ºC ± 5ºC. If the test should be performed at high or low temperatures, the test specimens must be placed in an environment that will ensure the required temperature. The test specimen should be examined immediately afterward within 5 seconds.

The locations for making the test specimens and the temperature at which they will be tested should be in accordance with standard ISO 15614, while the dimensions and the test principle should be in accordance with standard EN ISO 9016 [4]. However, the test temperature, type, location and size of the test specimen, and notch orientation shall be in accordance with the required application.

Impact test specimens should have the following characteristics:

– 1st character U: Charpy U-notch.
V: Charpy V-notch.

– 2nd character W: Notch in the weld metal; the reference line is the centre line of the weld at the position of the test specimen.
H: Notch in the heat affected zone; the reference line is the fusion or the joint line (notch will include HAZ).

– 3rd character S: Notched face parallel to the surface.
T: Notch through the thickness.

– 4th character a: Tthe distance between the notch and the reference line.

– 5th character b: The distance between the weld joint face to the nearer face of thetest specimen.

In order to test a fully welded joint, the standard ISO 15614-14 requires the test specimens with VWT and VHT marking. From each specified location, each set shall be comprised of three specimens (Figure 9).

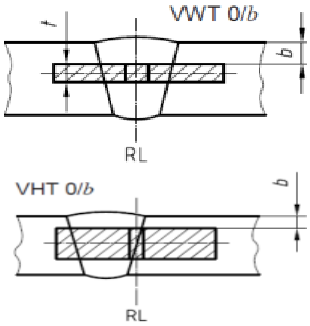



**Fig. 9.** Locations of the impact test specimens

The test specimens with Charpy V-notch shall be used and sampled from a maximum of 2 mm below the surface of the base material and transverse to the weld.

The absorbed energy shall be in accordance with the appropriate base material. The average value of the three specimens shall meet the specified requirements. For each notch location one individual value may be below the minimum average value specified, provided that it is not less than 70 % of that value [4].

The impact test specimens are made by machining from the middle part of the welded plate, Figure 2 zone 4, while the dimensions and its tolerances shall be in accordance with standard EN ISO 9016 (Table 5).

Table 5

*Dimensions and tolerances of impact test specimens [12]*

| Term (description) | U-notch test specimen | | V-notch test specimen | |
|---|---|---|---|---|
| | Nominal dimensions | Machining tolerances | Nominal dimensions | Machining tolerances |
| Length | 55 mm | ± 0.60 mm | 55 mm | ± 0.60 mm |
| Heigth | 10 mm | ± 0.11 mm | 10 mm | ± 0.60 mm |
| Width | | | | |
| ─ standard test specimen | 10 mm | ± 0.11 mm | 10 mm | ± 0.11mm |
| ─ rediced thickness test specimen | / | / | 7.5 mm | ± 0.11mm |
| ─ rediced thickness test specimen | / | / | 5 mm | ± 0.06 mm |
| Notch height | 5 mm | ± 0.09 mm | 8 mm | ± 0.06 mm |
| Notch radius | 1 mm | ± 0.07 mm | 0.25 mm | ± 0.025 mm |
| Notch angle | / | / | 45° | ± 2° |
| Distance between the notch axis and the ends of the test specimens | 27.5 mm | ± 0.42 mm | 27.5 mm | ± 0.42 mm |
| Angle between the planes of the welded sample and the test specimen | 90° | ± 2° | 90° | ± 2° |

### 3.5. *Hardness test*

According to the standard ISO 15614-14, the welded joint performed by hybrid laser arc welding is not subject to a hardness test, unless otherwise specified in the relevant application standard. If the hardness test is required should be done according to standard EN 9015-1 [4].

The hardness of the welded joint should be measured by Vickers method by applying a load of 98N (HV 10) on polished and etched test specimens whose test face is perpendicular to the weld axis. Normally, the test shall take the form of rows of hardness measurements, one for fillet welds and at least two rows for butt welds, the first one in the root area, and the second one in the cover pass area [11].

Hardness values should be determined for the weld metal, HAZ and base material in order to evaluate the range of hardness values across the welded joint [3].

The number of rows depends not only of the type of the weld, but also on thickness of the base material. For material thickness ≤ 5 mm, only one row is performed at a depth of < 2 mm below the upper surface of the welded joint. For a base material thickness over 5 mm, two rows should be performed at a depth of < 2 mm below the lower and upper surfaces of the welded joint [4]. Should this be insufficient for an adequate assessment of the welded joint hardness, additional rows shall be performed in the area between the root and cover pass. The arrangement of the rows of hardness measurements shall be as shown in Figure 10 [4, 11].

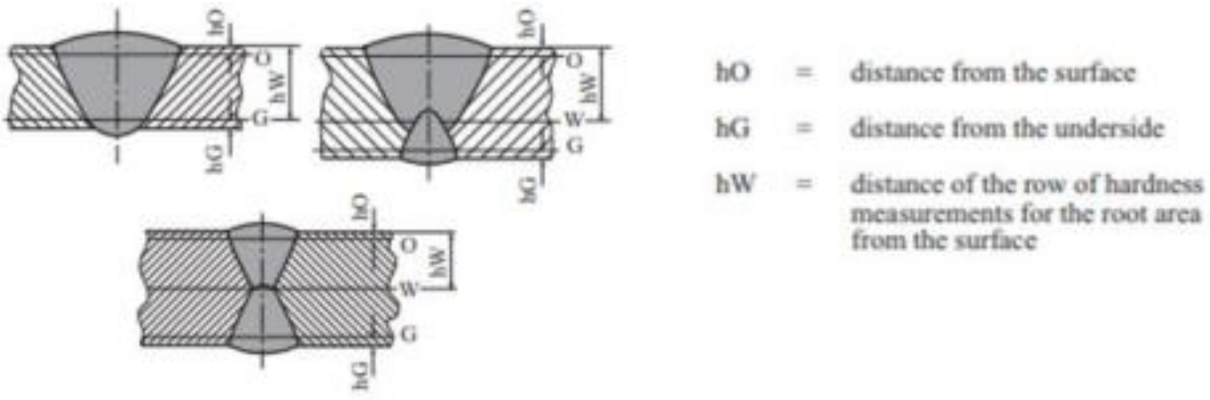



**Fig. 10.** Hardness testing with rows of hardness measurements [11]

For hardness test, certain guidelines should be met, for each row, the measurements should be done in three zones, the weld (3), the HAZ (2), and the base material (1), and at least 3 individual indentations should be taken in each area (Figure 11). In the HAZ the first indentation shall be placed as close to the fusion line as possible [4, 11, 14].

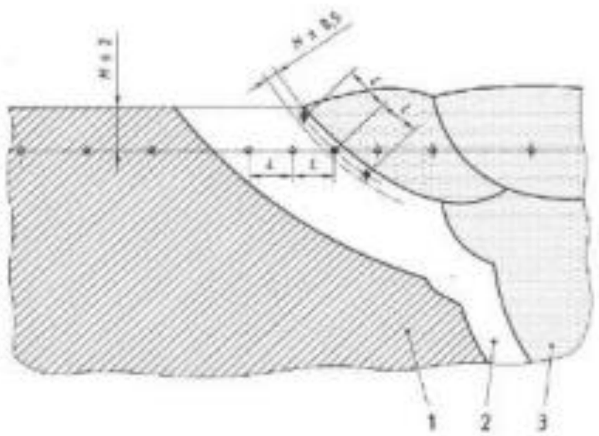



**Fig. 11.** Location of the indentations in butt welds in ferrous metals [13]

## 4. CONCLUSION

The introduction of new welding techniques and technologies leads to creation and development of new standards and procedures that confirm the quality of the welded joint.

Hybrid laser arc welding – HLAW, is a relatively new welding process that provides several advantages over conventional welding processes but has not yet been sufficiently elaborated and researched. For a better understanding of the hybrid process, additional research should be carried out in the field of welding technology, and the only way for verification is the production and testing of test specimens according to the prescribed norms and standards.

The test specimens used to prove the quality and mechanical characteristics of the welded joint performed by HLAW process are very similar to the test specimens of the conventional welding processes. However, there are certain deviations and additions that are prescribed in standard ISO 15614-14: Specification and qualification of welding procedures for metallic materials – Welding procedure test – Part 14: Laser-arc hybrid welding of steels, nickel and nickel alloys. According to standard ISO 15614-14, the mechanical tests that can be destructive and non-destructive are the primary indicator of the quality of the welded joint and the qualification of the welding technology.

The test specimens for tensile test of the welded joint are prescribed in standard ISO 4136 and they can be technical or standardized, the second type can have a cylindrical or prismatic cross-section, heat treatment shall not be applied to the welded joint or to the test specimen unless previously specified.

The bend test aims to check the deformation capabilities of the welded joint and should be performed according to standard ISO 5173, the dimensions of the test specimens depend on the base material thickness. Heat treatment shall not be applied to the welded joint or the test specimen unless previously specified.

The impact test of the welded joint is performed by the Charpy method on square cross-section test specimens with a V or U-notch and manufactured according to the standard ISO 9016.

The locations for making the test specimens and the temperature at which they will be tested should be in accordance with standard ISO 15614-14, more precisely, from each location set of three test specimens with marked VWT and VHT should be made.

According to the standard ISO 15614-14, the welded joint performed by hybrid laser arc welding is not subject to a hardness test, unless otherwise specified in the relevant application standard. If the hardness test is required should be done according to standard EN 9015-1, in the form of rows of hardness measurements in the weld metal, HAZ, and base material.

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