**Goce Delcev University – Stip**
**Faculty of Mechanical Engineering**


**Topic**

# Increased efficiency and energy saving/sustainability when welding steel "S355" with a thickness of 15.0 mm

**Experimental approach**

## Elimination of preheating by determining suitable welding parameters


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## 1. Introduction

The steel and metalworking industry in Germany comprises around 5,000 companies with around 500,000 employees. The industry is one of the ten largest and extremely medium-sized economic sectors in Germany. Around 98 percent of the companies employ fewer than 500 people. The industry processes around 20 million tons of steel per year with a turnover of around 80 billion euros.

In addition to various services, such as the mechanical processing of steel and aluminum parts and their special surface treatment, products and services are classic consumer goods, capital goods but above all products that are directly used as preliminary products in the production of downstream industrial sectors.

These include, above all, forgings and sheet metal parts, powder metallurgy products, springs, fasteners, support elements, pressure vessels, steel tubes, bright steel, Cold-rolled strip, wire and more Products.

Fig. 1: Grandstand roofing Zentralstadion Leipzig; Source SLV Hall

According to data from the Federal Statistical Office, the production of steel and metal processing companies in Germany weakened by 12.8 percent in 2020 compared to the previous year. Exports also fell by around 13.9 percent in 2020, due to the Covid19 pandemic. This development was accompanied by a reduction in production capacity utilization to currently around 78 percent. [1]

The unalloyed steel S355 according to DIN EN 10025-2 with a minimum strength of 355MPa yield strength (Re) (maximum load in the elastic range) is increasingly used in the steel processing industry. This replaces the unalloyed structural steel S235 according to DIN EN 10025-2 with a significantly lower minimum strength of 235MPa, especially in steel, container, pipeline, crane and vehicle construction. Fig. 2 shows the course of the stress-strain behavior for an unalloyed structural steel.



[1] : cf. Wirtschaftsverband Stahl- und Metallverarbeitung e.V. WSM

Due to the higher strength properties of the material S355 compared to the material S235, the use of this material enables considerable savings in material and production costs.There The products to be produced Products with approx. 35% lower wall thicknesses made And that is what we are talking about. When joining the components, "welding" is mainly used, here for economic reasons, in particular metal active gas welding (MAG). As a result of the higher strength properties, however, increase the demands on the processing process during welding processing.s in particular with regard to suitable welding parameter. The determination of suitable welding parameters in compliance with corresponding quality criteria is the basis The VThis is the case in the United Kingdom..

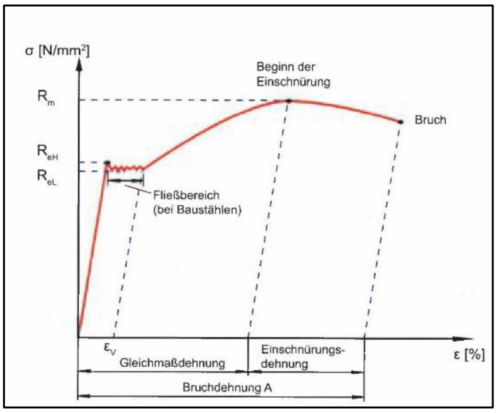



Fig. 2: Stress-strain behaviour
Unleg. Structural steel; Source DVS-IIW course part 1; 2016

## 2. Initial situation and objectives

In particular, bIn the manufacture of steel structures in bSupervisionEn (bridges, halls, Steel stairs etc.) are often used by structural engineers Semi-finished products (sheets) from the Called Material S355J2+N dimensioned with a thickness of 15.0mm. Due to the large material thickness (t=15 mm) experienced the components when using unfavorable welding parameters as a result of the Welding a relatively high heat dissipation speed. The result is a Possible Hardening as well as Embrittlement in the field of Heat affected zone (see Fig. 3). The Material is thus in the area of the joining zone for the intended application is unusable.

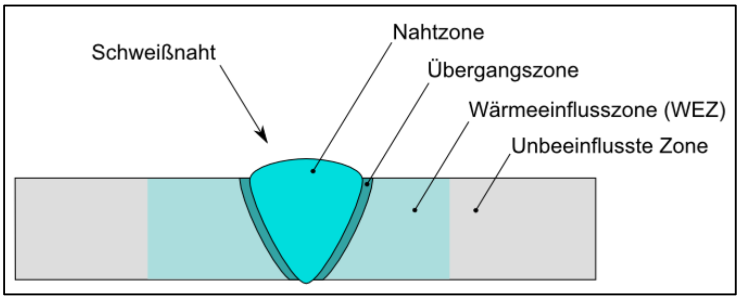



Fig. 3: Schematic structure of a welded joint; Source: Maschinenbau-Wissen.de

In order to counteract too rapid cooling, the components to be welded are usually preheated before welding. This preheating is carried out, for example, with a gas burner or by means of induction heating by alternating electromagnetic fields, which induce eddy currents in the workpiece and convert them into heat through the magnetization losses. However, these preheating processes are at the expense of economic efficiency and, last but not least, the environment. Experience values of the HWK Koblenz show that the process of preheating with a volume of up to 20% is significantly involved in the total production time with regard to welding. [Source: HWK-Koblenz]

The aim is to optimize the welding parameters in this A by means of a series of tests in such a way that preheating can be dispensed with. For this purpose, the heat input during welding must be increased to a level that is equivalent to preheating. The associated reduction in heat dissipation should lead to a welding result equivalent to preheating. However, it should be noted that too much heat input causes a negative influence on the material structure with unfavorable strength and toughness properties. As a result of the aforementioned aspects, therefore, a welding parameter window results due to the mechanical-technological properties "hardening" and "softening". This welding parameter window has to be determined in the present work.

## 3.Fundamentals of materials technology

The following chapter gives an overview of the material fundamentals of steel S355J2+N which serves as a test object in this paper.

### 3.1 Overview

Steels are characterized by their ability to solidify. This mechanism is linked to an obstruction of the mobility of dislocations. This refers to the obstruction of ion movements in the metal lattice. This results in five mechanisms that cause an increase in strength. These are:

– hardening,
– strain hardening,
– **solid solution hardening (alloy formation),**
– **hardening by lattice transformation (formation of martensite),** and
– grain refinement (formation of grain boundaries) [2]



[2] : cf. Roos, E; Enamel

For reasons of complexity, only those strength-enhancing mechanisms are explained below, which are essentially used in the material S355 .

Solidification by solid solution solidification

The solid solution solidification is achieved by depositing or substituting (exchange) foreign atoms in the base lattice. The different atomic volumes in a substitution solid solution create a constant elastic stress field that can strongly influence the movements of the dislocations. A similar effect emanates from a strongly strained solid solution. In unalloyed structural steels, for example, the strength increases sharply with increasing carbon content, but this has a negative effect on the weldability of these materials. Depending on the type, quantity and size of the incorporated atoms, there may be a simultaneous increase in strength and toughness values (e.g. in the case of alloying with nickel) or a simultaneous sharp drop in the notched bar impact work. [2]

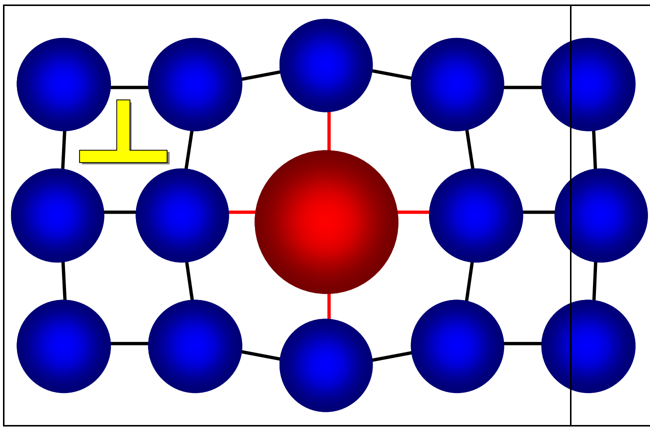


Figure 4: Principle of solidification by solid solution solidification (dislocation movement is hindered by foreign atoms) [Source DVS-IIW course part 3; 2016]

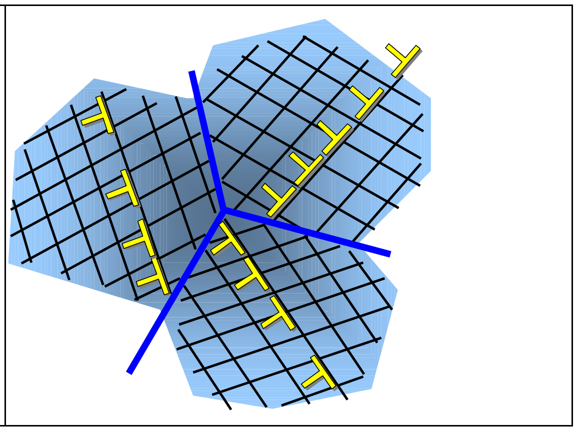


Figure 5: Principle of solidification by grain boundaries (grain boundaries represent obstacles to the dislocation movement) [Source DVS-IIW course part 3; 2016]

Solidification by lattice transformation due to high cooling rates

Solidification by lattice transformation is the process of classic hardening of steel. Here, cooling rates are greater than $v_{ukrit}$ increasingly suppresses the diffusion of carbon. By the forced dissolution of this element, it occurs as a result of the martensitic transformation ("Fold down the structure") to a significant increase in the dislocation density and thus to micro and macro residual stresses, which cause an increase in the strength properties. Depending on carbon content and cooling rate reduce As a rule, the toughness properties are clear. [3]



[3] : cf. Roos, E; Enamel

### 3.2 Effects of temperature-time curve during welding

The temperature cycles occurring during welding (temperature-time-curve) have, on the basis of the explanations in chapter 3.1, a decisive influence on the mechanical properties in the weld metal and in the heat-affected zone (see Fig. 3.1). The temperature cycles themselves depend on the following welding conditions:

- Thickness
- Seam shape
- Line energy (welding current x welding voltage/ welding speed)
- Preheating temperature
- Ambient temperature
- Layer structure

The temperature-time curve occurring during an arc passage at a defined point consists of a short heating phase and a generally much longer cooling phase. When the arc approaches, the temperature rises rapidly to a maximum value and drops again after passing through the arc, whereby the cooling rate decreases steadily. While the same peak temperatures occur everywhere in the weld metal, the different areas of the heat-affected zone are heated to different peak values; their height decreases with increasing distance from the melting zone. The mechanical properties of the weld metal are further determined by:

- the chemical composition
- the rate at which cooling from the liquid phase occurs
- the peak temperature reached during welding

Experience has shown that high peak temperatures lead to the most unfavourable microstructure conditions and mechanical properties. It is therefore sufficient to consider the temperature cycles with the highest peak temperature, which occur directly next to the melting line of the heat-affected zone. Their peak temperature is equal to the melting temperature of the respective material. It can therefore be assumed that the mechanical properties in the heat-affected zone are determined by the cooling process after the arc passage. The cooling time $t_{8/5}$ has proven itself in the treatment of material issues . This is the time it takes during the cooling of a welding bead and its heat-affected zone to pass through the temperature range of 800 °C to 500 °C. In this temperature interval, the essential transformation processes take place. When calculating the cooling times, a distinction must be made between three- and two-dimensional heat dissipation. When welding relatively thick workpieces, heat dissipation takes place three-dimensionally. The heat introduced via the arc can flow away in the workpiece plane and additionally in the direction of the workpiece thickness. This therefore has no effect on the cooling time. With two-dimensional heat dissipation, on the other hand, the heat flow takes place exclusively in the workpiece plane. In this case, the workpiece thickness is decisive for the cross-sectional area available for heat dissipation and thus has a pronounced influence on the cooling time. With three-dimensional heat dissipation, the heat-affected zone cools down much faster than with two-dim

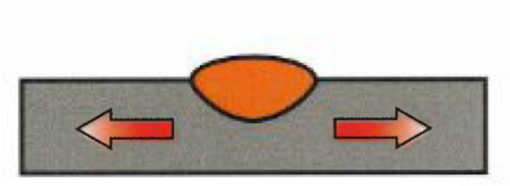


Fig. 6: Two-dimensional heat dissipation
Source DVS-IIW course part 1; 2021

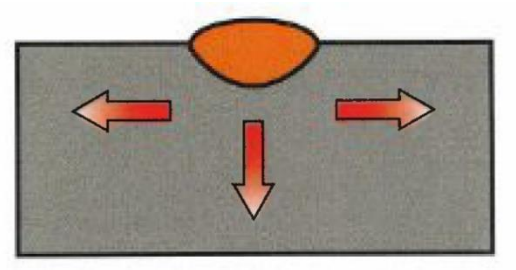


Fig. 7: three-dimensional heat dissipation
Source DVS-IIW course part 1; 2021

If the heat dissipation is three-dimensional and the cooling time is independent of the workpiece thickness, equation 1 is used for the calculation.

$$t_{8/5} = (6\,700 - 5\,T_o) \times Q \times \left(\frac{1}{500 - T_o} - \frac{1}{800 - T_o}\right) \times F_3$$ (Equation 1) [5]

If the heat dissipation is two-dimensional, i.e. the cooling time depends on the thickness of the material, equation 2 is used for the calculation.

$$t_{8/5} = (4\,300 - 4{,}3\,T_o) \times 10^5 \times \frac{Q^2}{d^2} \times \left[\left(\frac{1}{500 - T_o}\right)^2 - \left(\frac{1}{800 - T_o}\right)^2\right] \times F_2$$ (Equation 2) [5]

The sheet thickness at the transition from three- to two-dimensional heat dissipation is called the transition plate thickness $d_ü$. By equating the formulas for calculating the cooling time t8/5 for three- and two-dimensional heat dissipation, this can be determined. [5]



[4]: cf. Roos, E; Maile,
[5]: cf. DIN EN 1011-2

### 3.2.1 Line energy/heat input

The line energy stands for the amount of heat that will be introduced during welding. This depends on the material. It is of great importance for the hardening-sensitive Stahl S355 examined here. The calculation of the line energy is carried out according to equation 1:

$$E = \frac{U*I}{vw}$$ [Equation 3]

However, it must be borne in mind that not all the electrical energy taken from the power source can be supplied to the weld pool, but only a certain part depending on the welding process and welding conditions. However, only this energy, which is actually introduced into the weld seam area, has an influence on the solidification process in the weld metal and the thermally induced structural changes in the heat-affected zone. Therefore, it is necessary to take into account the energy losses in a differentiated view.

This can be done by extending the distance energy E by a factor of η, which results from the ratio of the energy introduced into the seam area to the energy supplied to the welding process. [21] The heat input Q defined in this way is calculated according to equation 2:

$$Q = \eta * E = \eta * \frac{U*I}{vw}$$ [Equation 4]

The line energy can only be controlled within very narrow limits via the current and the welding voltage, because in order to achieve a certain deposition rate, a certain electrical voltage with a dependent current must be used. The only variable in the above formula is thus the welding speed. However, due to a usually required weld seam thickness, there is a lower and upper limit value with regard to the welding speed $v_w$. [6]

## 4. Experimental studies

As a basis for carrying out the welding tests, appropriate boundary conditions had to be defined in addition to the base material S355. The subsequent tests and material tests are described in detail as follows.



[6] : cf. DVS-IIW Course Script Part 1

### 4.1 Component/Geometry

According to the Koblenz Chamber of Crafts, the dominant type of seam and type of joint is the so-called one-sided fillet seam at the T-joint. In particular, this is used in the field of building supervision, such as in the manufacture of stairs, railings, halls and bridges. The weld joint shown in Figure 8 serves geometrically as the basis for the welding tests carried out.

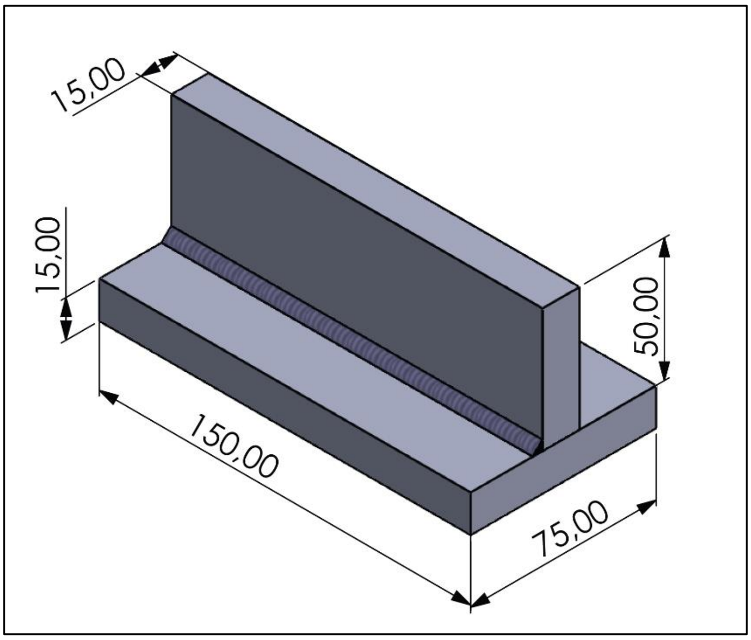



Fig.8: Fillet seam at the T-joint; CAD model; Source: HWK-Ko

### 4.2 Parameter definition

If welding work is to be carried out in the area of building inspectorates, normatively regulated test welding is required in advance by the executing companies as part of quality assurance. If these are positive in terms of geometric and metallurgical characteristics, the welding parameters used in the test welds can be used. Since the Koblenz Chamber of Crafts is aware of these parameters, they serve as a starting value for the production of the test welds within the scope of this work.

It should be noted that in the known test welds basically a preheating with a temperature of 120 ° C was used. Since this is to be eliminated in the context of this elaboration, this parameter is set to room temperature (20 ° C). The starting value in this series of tests represents the limit value with the highest heat input. The test parameter list shown below (see Table 1) ends with a limit value of the heat input "downwards", which, according to the Koblenz Chamber of Crafts, is to be regarded as a "very low" heat input. Whether the bandwidth of the selected parameter window proves to be sufficient is shown by the evaluations of the welding tests. It may be necessary to extend the number of test welds.

| Parameter | Versuch 1 | | Versuch 2 | | Versuch 3 | | Versuch 4 | | Versuch 5 | | Versuch 6 | | Versuch 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Spannung U** | 25 | V | 25 | V | 25 | V | 25 | V | 25 | V | 25 | V | 25 | V |
| **Stromstärke I** | 250 | A | 250 | A | 250 | A | 250 | A | 250 | A | 250 | A | 250 | A |
| **Schweißgeschwindigkeit $V_{weld}$** | 45 | cm/min | 50 | cm/min | 55 | cm/min | 60 | cm/min | 65 | cm/min | 70 | cm/min | 75 | cm/min |
| | | | | | | | | | | | | | | |
| **Streckenenergie E** | 0,83 | kJ/mm | 0,75 | kJ/mm | 0,68 | kJ/mm | 0,63 | kJ/mm | 0,58 | kJ/mm | 0,54 | kJ/mm | 0,50 | kJ/mm |
| **Wärmeeinbringung Q** | 0,67 | kJ/mm | 0,60 | kJ/mm | 0,55 | kJ/mm | 0,50 | kJ/mm | 0,46 | kJ/mm | 0,43 | kJ/mm | 0,40 | kJ/mm |
| **Grundwerkstoff** | S355J2 nach DIN EN 10025-2 | | S355J2 nach DIN EN 10025-2 | | S355J2 nach DIN EN 10025-2 | | S355J2 nach DIN EN 10025-2 | | S355J2 nach DIN EN 10025-2 | | S355J2 nach DIN EN 10025-2 | | S355J2 nach DIN EN 10025-2 | |
| **Schweißzusatzwerkstoff** | G3Si1 nach DIN EN ISO 14341 | | G3Si1 nach DIN EN ISO 14341 | | G3Si1 nach DIN EN ISO 14341 | | G3Si1 nach DIN EN ISO 14341 | | G3Si1 nach DIN EN ISO 14341 | | G3Si1 nach DIN EN ISO 14341 | | G3Si1 nach DIN EN ISO 14341 | |
| **thermsicher Wirungsgrad für das Metallschutzgasschweißen (18% $CO_2$ in Argon)** | 80 | % | 80 | % | 80 | % | 80 | % | 80 | % | 80 | % | 80 | % |

Table 1: Test parameters

Based on the welding parameters mentioned above, the transition plate thickness shown in 3.2 can be determined by equating formula 1 and 2 to 5 with d = $d_Ü$.

$$t_{8/5} = \frac{Q^2}{4\pi\lambda\varrho c d^2} \times \left( \frac{1}{(500 - T_o)^2} - \frac{1}{(800 - T_o)^2} \right)$$ (Equation 1)

$$t_{8/5} = (4\,300 - 4{,}3\ T_o) \times 10^5 \times \frac{Q^2}{d^2} \times \left[ \left( \frac{1}{500 - T_o} \right)^2 - \left( \frac{1}{800 - T_o} \right)^2 \right] \times F_2$$ (Equation 2)

$$dü = [\frac{4300-4{,}3\ To}{6700-5\ To} * 105\ Q * (\frac{1}{500-To} + \frac{1}{800-To})]^{0,5}$$ (Equation 5) [13]

The calculation was carried out with the help of the calculation software on www.erl-gmbh.de The corresponding seam factors are stored in DIN EN 1011-2 and in the calculation software. The maximum of the transition plate thickness is for test parameters 1 with dü =11.9mm, the minimum for test 7 with dü= 9.27mm. Since the wall thickness of the test series is 15.0mm and thus above the transition plate thickness from the test parameters, a three-dimensional heat dissipation takes place.



[13]: cf. erl-gmbh

### 4.3 Material verification by optical emission spectrometry

The material S355J2+N is used for the welding tests. In order to ensure comparability of the tests, all tests are carried out on semi-finished products of the same batch of materials. DIe Consistency of the underlying materialit with the requirements of the material order is on the part of the Stahlhby a supplied material test certificate. This includes the u.a. the chemical properties of the present semi-finished product. In order toe to verify, became optical emission spectrometry was carried out at the Koblenz Chamber of Crafts. Table 2 provides proof of positive match.


Fig. 9: Performing the optical
Emission spectrometry Source: HWK-KO

| **Spektralanalyse (Dargestellt sind die Mittelwerte aus 5 Einzelmessungen)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Prüfmaschine | | | | | PMI Master Smart | | | |
| Kalibrierung | | | | | Formblatt Prüfmittelüberwachung | | | |
| **Element** | **Fe** | **C** | **Si** | **Mn** | **P** | **S** | **Cu** | **Al** |
| Analyse entsprechend DIN EN 10025-2 (Massenprozent) | **Rest** | **<=0,27** | **<=0,6** | **<=1,7** | **<=0,035** | **<=0,035** | **<=0,6** | **<=0,02** |
| Zeugnis Lieferant | 97,7 | 0,194 | 0,246 | 1,45 | 0,0249 | 0,0232 | 0,0972 | 0,0276 |
| HWK | 97,5 | 0,198 | 0,229 | 1,51 | 0,0264 | 0,0219 | 0,0886 | 0,0241 |
| **Werkstoff: (chemisch)** | | **S355J2** | | | | | | |

Table. Fig. 2: Results of optical emission spectrometry

### 4.4 Manufacture of test pieces

In order to implement the parameters specified in 4.2 precisely and reproducibly during the production of the test welds, a fully mechanical welding process was used. Fig. 10 shows the welding robot used in articulated arm design. As part of the internship, I was able to acquire programming for the production of simple welded assemblies. The programming is based on a "point to point" control. The corresponding spatial points are set in the orthogonal coordinate system by direct approach with the robot with a control console. This procedure is called the teach-in process.

Fig. 10: Welding robot in articulated arm design; Photo HWK-Ko

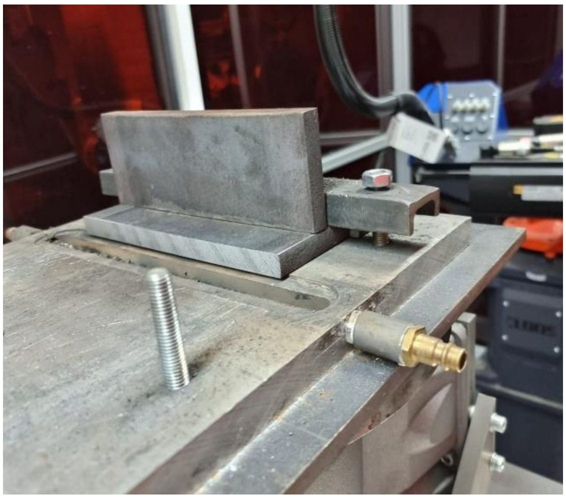


Fig. 11: Test setup; Photo HWK-Ko

### 4.5 Visual inspection

Visual inspection is a non-destructive method for weld seam inspection. This can be done before welding (weld seam preparation) after welding or during the welding process. The early detection of external defect characteristics enables rapid feedback to the manufacturing process. The decision as to whether or not an irregularity is still permissible shall be determined on the basis of a criterion to be agreed in advance. DIN EN ISO 5817 is the set of rules used in almost all welding applications in which steels are processed. Three different evaluation groups (quality levels) are distinguished: evaluation group D for subordinate welded joints, evaluation group C for statically stressed welded joints and evaluation group B for changing loads. Since the scope of application of the topic examined here lies in standard applications in steel construction, and these are usually statically stressed, evaluation group C was used as a basis for the investigations carried out. [7/12]

<u>Results of the visual inspection:</u>

The irregularities in the test welds are within the limit values according to DIN EN ISO 5817 evaluation group C. The corresponding visual inspection report is set out in **Annex A**.



[7] : cf. DIN EN ISO 17637
[12] : cf. DIN EN ISO 5817

### 4.6 Surface crack detection

The penetrant test is a Non-destructive Method for detecting irregularities open to the surface and usually not due to the visual inspection findable are. Due to the capillary action, the following fills too very fine irregularities such as cracks or binding defects with the penetrant which, after pre-cleaning, is applied to the surface to be tested with a spray can or brush is applied. After a regulated penetration time (usually 15min) the surface with water cleaned without washing out the penetrant from the irregularities. A developer who is sprayed onto the test piece surface then sucks the penetrant out of the irregularities. The resulting „Bleeding“ displays possibly present Error or irregularityEn at. Fig. 12 shows an example of a typical display as Clarification. [8]

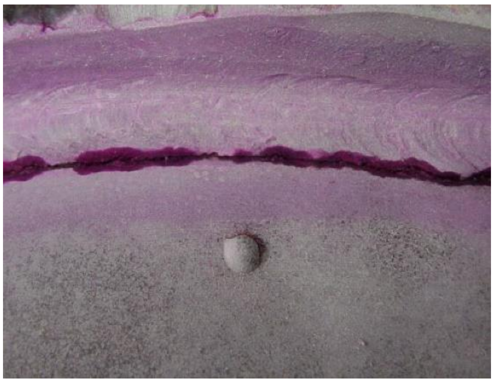


Fig. 12: Display during a penetrant test; Source HWK-Ko

<u>Results of the surface crack test:</u>

The irregularities in the test welds are within the limit values according to DIN EN ISO 5817 evaluation group C. The corresponding penetrant test report is set out in **Annex A**.

### 4.7 Metallographic examination

The macro grinding examination is a destructive test method for the local assessment of welded joints in cross-section. For this purpose, a welded sample is separated perpendicular to the weld seam by sawing. Subsequently, the surface is ground up to a grain size of K1000. By subsequent etching with, for example, alcoholic nitric acid, different microstructures are dissolved from the surface to varying degrees. The resulting raised and recessed areas on the surface lead to directed or diffuse Reflections of the incident light on the sample surface. Due to the resulting contrast, Burn-in conditions, the heat-affected zone and the location and type of defects or irregularities, such as cracks, pores, slag, bonding defects, can be identified. Fig. 13 shows an example of a macro grinding of the test welds. [9]


Fig. 13: Metallographic examination

[8] : cf.  DIN EN ISO 3452-1

<u>Results of the metallographic examination:</u>

The irregularities in the test welds are within the limit values according to DIN EN ISO 5817 evaluation group C. The corresponding metallographic test report is given in **Annex B**.

### 4.8 Vickers hardness test

According to Adolf MARTENS (1850-1914), hardness is the resistance of one body to the penetration of another (harder) body. The hardness cannot be measured directly, but is derived from primary measurands (e.g. test load, penetration depth, Impression surface) is derived. In the Vickers hardness test method, the hardness value is determined by a Length characterizing hardness impression described. An indenter made of diamond in the form of a straight pyramid with a square base with a Angle α of 136° between opposite surfaces is pressed into the surface of a sample and the diagonals d1 and d2 of the indentation in the surface after removal of the test load F lags behind, measured (see Fig. 14) The corresponding test parameters are specified in DIN EN ISO 9015-1 and DIN EN ISO 6507-1 regulated. [10/11] Fig. 14 shows the corresponding zones of the welded joint in which the hardness testEn Wasn.

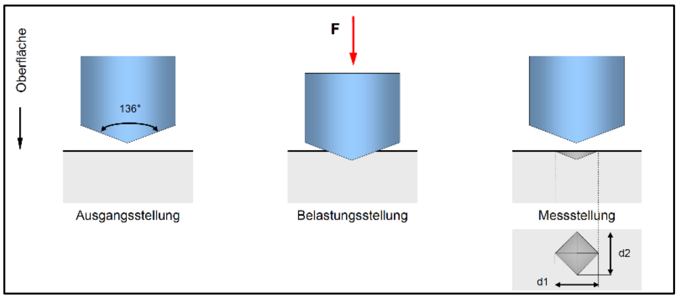


Fig. 14: Hardness testing according to Vickers measuring principle

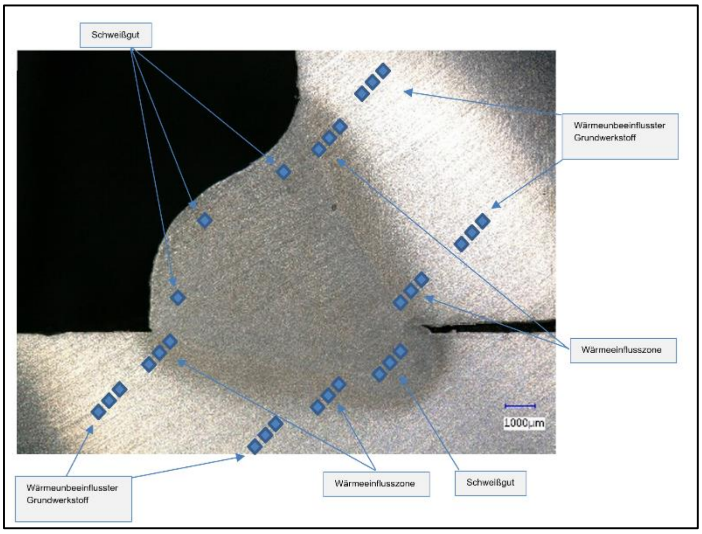


Fig. 14: Hardness testing Laboratories

The corresponding hardness test reports are given in **Annex C**.



[9] cf. DIN EN ISO 17639
[10] cf. DIN EN ISO 9015-1
[11] cf. DIN EN ISO 6507-1

## 5. Evaluation of test results

The entire test series shows positive test results in visual inspection, surface crack inspection and metallographic examination. It can thus be stated that the welding parameters used can be regarded as positive with regard to their suitability with regard to the above-mentioned tests and meet the required quality characteristics according to DIN EN ISO 5817 evaluation group C.

Table 3 shows the significant influence on the hardness in the heat-affected zone due to the welding parameter modification. Thisshows the hardness results that deviate from the mean value of the heat of the unaffected base material (hardness=182HV10).

| Test welds | | | | |
|---|---|---|---|---|
| **Sample** | **Heat input [kJ/mm]** | **Reference value of hardness [HV10]** | **Assessment** | **Hardness of the base material mean value (not heat-influenced) [HV10]** |
| 1 | 0,67 | 163,8 | too low | 182 |
| 2 | 0,6 | 171 | too low | |
| 3 | 0,55 | 177,9 | too low | |
| 4 | 0,5 | 199,3 | optimal | |
| 5 | 0,46 | 213,1 | OK | |
| 6 | 0,43 | 221,6 | OK | |
| 7 | 0,4 | 231,8 | OK | |

Table 3: Influence of heat input/hardness

With increasing welding speed, the heat input decreases. A resulting reduced t8/5 time leads to an influence on the structural transformationprocesses which are directly related to the resulting hardness. Hardness values below the hardness of the non-heat-affected base material cannot be accepted due to softening. This is regulated normatively by DIN EN ISO 15614-1 (Requirement and qualification of welding processes for metallic materials – welding method testing). Thus, the welding parameters used in welding tests 1-3 are not applicable with regard to sufficient hardness and strength properties. The welding tests 4-7 show hardness values above the basic hardness of the material used S355J2+N. Since the ductility properties are negatively influenced with increasing hardness, caused by microstructure conversion processes, the best possible hardness is the one closest above the basic hardness of the material

S355J2+N (here 182HV10). In the test series, this is reflected in sample 4 with a maximum hardness in the heat-affected zone of 199.3HV10. Diagram 1 shows the relationship between hardness and heat input.

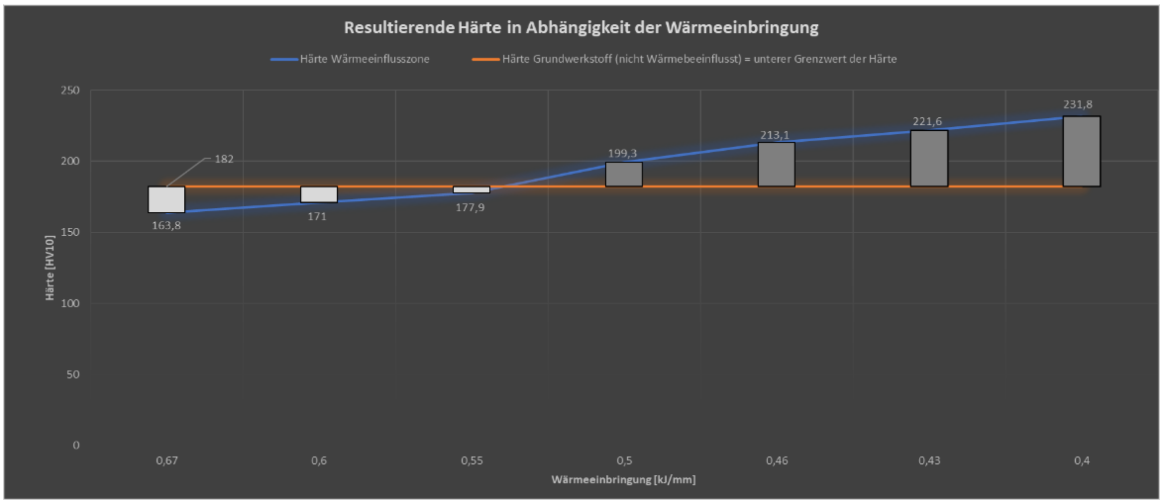



Diagram 1: Hardness via heat input

### 6. Conclusion

The present work shows that suitable parameters can dispense with preheating during welding of the hardening material S355J2+N with a thickness of 15.0mm. This increases energy efficiency and cost-effectiveness of the welding manufacturing process in this application. The possibility of extrapolating the present results to wall thicknesses above 15.0mm including the two- or three-dimensional heat dissipation can take place. If the welding parameters classified as "optimal" are adhered to, all wall thicknesses above 15.0mm can be welded without preheating due to the determined transition plate thickness. However, it is imperative to note that the material batch, and thus the possibly deviating chemical compositions, can influence the result, in particular the resulting hardness.

Since the investigated connection can be regarded as "standardized" and has high relevance in the metalworking trades, the test results will be used in the future in training and further education as well as welding technology consulting of the Koblenz Chamber of Crafts.

## 7. Annex A

### Inspection results of the visual inspection

| **Visual inspection** | DIN EN ISO 17637 | | | Measuring devices: Seam gauges |
|---|---|---|---|---|
| Fillet seam – top layer | | | | |
| Illuminance test station: >600lx | | | | |
| Sample | Irregularities<br>Evaluation according to DIN EN ISO 5817 Evaluation Group C | | | Assessment |
| 1 | | | | without complaint |
| 2 | | | | without complaint |
| 3 | | | | without complaint |
| 4 | | | | without complaint |
| 5 | | | | without complaint |
| 6 | | | | without complaint |
| 7 | | | | without complaint |
| Remarks: - | | | | |

### Test results of the surface crack test

| **Penetrant testing** | DIN EN ISO 3452 |
|---|---|
| Request | DIN EN ISO 5817 Evaluation group C |
| Measuring devices | Helling Standart-Check |
| Evaluation group: | see requirements |
| Amount of inspection: | 100% weld + WEZ**) |
| Pre-cleaning: | Helling Standart-Check; Ch.Nr, 27475/09/2014 |
| Penetrants: | Helling Standart-Check; Ch.Nr, 25443/01/2014 |
| Intermediate cleaner: | Helling Standart-Check; Ch.Nr, 27475/09/2014 |
| Developer: | Helling Standart-Check; Ch.Nr, 27478/10/2014 |
| Intrusion system: | DIN EN 571-1 IIC-d |
| Penetration time | 15min |
| Assessment dates: | 1.: After drying the developer; 2.: After 2min |

| Sample | Irregularities (tick as appropriate) | | | | | Assessment |
|---|---|---|---|---|---|---|
| | 100 | 104 | 2017 | 506 | 517 | |
| 1 | | | | | | without complaint |
| 2 | | | | | | without complaint |
| 3 | | | | | | without complaint |
| 4 | | | | | | without complaint |
| 5 | | | | | | without complaint |
| 6 | | | | | | without complaint |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | | | | | | without complaint |
| Remarks: - | | | | | | |

**Appendix B**

**Test results of the metallographic examination**

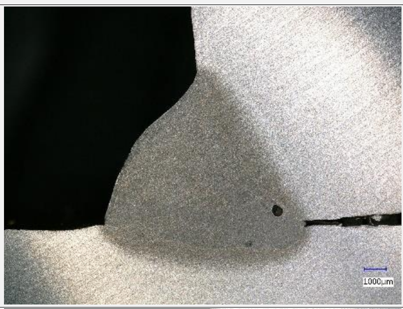
| **Metallographic examination** | DIN EN ISO 17639 | Measuring devices: | Microscope Keyence VHX 5000 |
|---|---|---|---|
| Corrosive: alcoholic nitric acid<br>Objective magnification: 20X | | | |

| Sample | Macrostructure | Irregularities<br><br>Evaluation according to DIN EN ISO 5817 Evaluation Group C | Assessment |
|---|---|---|---|
| 1 |  | - | without complaint |
| 2 |  | - | without complaint |
| 3 |  | - | without complaint |

| | | | |
|---|---|---|---|
| 4 |  | - | without complaint |
| Remarks: - | | | |

**Appendix B**

**Test results of the metallographic examination**

| **Metallographic examination** | DIN EN ISO 17639 | Measuring devices: | Microscope Keyence VHX 5000 |
|---|---|---|---|
| Corrosive: alcoholic nitric acid<br>Objective magnification: 20X | | | |
| Sample | Macrostructure | Irregularities<br><br>Evaluation according to DIN EN ISO 5817 Evaluation Group C | Assessment |
| 5 |  | - | without complaint |
| 6 |  | - | without complaint |

| | | | |
|---|---|---|---|
| 7 |  | - | without complaint |
| Remarks: - | | | |

## Appendix C

### Test results of the hardness test

| | | | | |
|---|---|---|---|---|
| **Vickers hardness test** | | | **DIN EN ISO 9015-1** | |
| | | | **DIN EN ISO 6507-1** | |
| **Testing machine** | Schenck Trebel Hardness Tester 38532, MPA NRW 43 0453 | | | |
| **Test load F** | 98,065 | [N] | | |
| **Request:** | DIN EN ISO 15614-1; Hardness <= 380HV10 | | | |
| **Sample 1** | | | | |
| **Hardness test lf.** | **$d_{\text{Measured value}}$** | **$d_{is}$** | **$d_{is}^2$** | **HV** |
| **1 GW** | 44,5 | 0,32 | 0,10 | **183,5** |
| **2 GW** | 44,6 | 0,32 | 0,10 | **182,7** |
| **3 GW** | 44,8 | 0,32 | 0,10 | **181,1** |
| **4 HAZ** | 45,5 | 0,33 | 0,11 | **175,6** |
| **5 HAZ** | 46,3 | 0,33 | 0,11 | **169,6** |
| **6 HAZ** | 46,8 | 0,33 | 0,11 | **165,9** |
| **7 SG** | 42,9 | 0,31 | 0,09 | **197,5** |
| **8 SG** | 43,1 | 0,31 | 0,09 | **195,7** |
| **9 SG** | 43,0 | 0,31 | 0,09 | **196,6** |
| **10 HAZ** | 47,1 | 0,34 | 0,11 | **163,8** |
| **11 HAZ** | 46,5 | 0,33 | 0,11 | **168,1** |
| **12 HAZ** | 46,4 | 0,33 | 0,11 | **168,8** |
| **13 GW** | 44,4 | 0,32 | 0,10 | **184,4** |
| **14 GW** | 44,8 | 0,32 | 0,10 | **181,1** |
| **15 GW** | 44,7 | 0,32 | 0,10 | **181,9** |
| GW: Base material | | | | |
| SG: weld metal | | | | |
| HAZ: Heat affected zone | | | | |
| **Assessment** | **fulfilled** | | | |

**Appendix C**

**Test results of the hardness test**

| | | | | |
|---|---|---|---|---|
| **Vickers hardness test** | | | **DIN EN ISO 9015-1** | |
| | | | **DIN EN ISO 6507-1** | |
| **Testing machine** | Schenck Trebel Hardness Tester 38532, MPA NRW 43 0453 21-8 | | | |
| **Test load F** | 98,065 | [N] | | |
| **Request:** | DIN EN ISO 15614-1; Hardness <= 380HV10 | | | |
| **Sample 2** | | | | |
| **Hardness test lf. Nr.** | **d** **Measured value** | **d** **is** | **d** $_{is}^{2}$ | **HV** |
| **1 GW** | 44,3 | 0,32 | 0,10 | **185,2** |
| **2 GW** | 44,8 | 0,32 | 0,10 | **181,1** |
| **3 GW** | 44,5 | 0,32 | 0,10 | **183,5** |
| **4 HAZ** | 44,6 | 0,32 | 0,10 | **182,7** |
| **5 HAZ** | 45,2 | 0,32 | 0,10 | **177,9** |
| **6 HAZ** | 45,9 | 0,33 | 0,11 | **172,5** |
| **7 SG** | 42,6 | 0,30 | 0,09 | **200,3** |
| **8 SG** | 42,9 | 0,31 | 0,09 | **197,5** |
| **9 SG** | 42,9 | 0,31 | 0,09 | **197,5** |
| **10 HAZ** | 46,1 | 0,33 | 0,11 | **171,0** |
| **11 HAZ** | 45,5 | 0,33 | 0,11 | **175,6** |
| **12 HAZ** | 45,3 | 0,32 | 0,10 | **177,1** |
| **13 GW** | 44,4 | 0,32 | 0,10 | **18 3.2** |
| **14 GW** | 44,8 | 0,32 | 0,10 | **182.6** |
| **15 GW** | 44,7 | 0,32 | 0,10 | **183.1** |
| GW: Base material | | | | |
| SG: weld metal | | | | |
| HAZ: Heat affected zone | | | | |
| **Assessment** | **fulfilled** | | | |

## Appendix C

### Test results of the hardness test

| | | | | |
|---|---|---|---|---|
| **Vickers hardness test** | | | **DIN EN ISO 9015-1** | |
| | | | **DIN EN ISO 6507-1** | |
| **Testing machine** | Schenck Trebel Hardness Tester 38532, MPA NRW 43 0453 21- | | | |
| **Test load F** | 98,065 | [N] | | |
| **Request:** | DIN EN ISO 15614-1; Hardness <= 380HV10 | | | |
| **Sample 3** | | | | |
| **Hardness test lf.** | **d** **Measured value** | **d** **is** | **d** **is**$^2$ | **HV** |
| **1 GW** | 44,6 | 0,32 | 0,10 | **182,7** |
| **2 GW** | 44,9 | 0,32 | 0,10 | **180,3** |
| **3 GW** | 44,5 | 0,32 | 0,10 | **183,5** |
| **4 HAZ** | 44,3 | 0,32 | 0,10 | **185,2** |
| **5 HAZ** | 44,9 | 0,32 | 0,10 | **180,3** |
| **6 HAZ** | 45,2 | 0,32 | 0,10 | **177,9** |
| **7 SG** | 42,5 | 0,30 | 0,09 | **201,2** |
| **8 SG** | 42,7 | 0,31 | 0,09 | **199,3** |
| **9 SG** | 42,3 | 0,30 | 0,09 | **203,1** |
| **10 HAZ** | 45,0 | 0,32 | 0,10 | **179,5** |
| **11 HAZ** | 45,1 | 0,32 | 0,10 | **178,7** |
| **12 HAZ** | 45,1 | 0,32 | 0,10 | **178,7** |
| **13 GW** | 44,4 | 0,32 | 0,10 | **18 2.7** |
| **14 GW** | 44,8 | 0,32 | 0,10 | **18 2.2** |
| **15 GW** | 44,7 | 0,32 | 0,10 | **181.8** |
| GW: Base material | | | | |
| SG: weld metal | | | | |
| HAZ: Heat affected zone | | | | |
| **Assessment** | **fulfilled** | | | |

## Appendix C

### Test results of the hardness test

| | | | | |
|---|---|---|---|---|
| **Vickers hardness test** | | | **DIN EN ISO 9015-1** | |
| | | | **DIN EN ISO 6507-1** | |
| **Testing machine** | Schenck Trebel Hardness Tester 38532, MPA NRW 43 0453 21- | | | |
| **Test load F** | 98,065 | [N] | | |
| **Request:** | DIN EN ISO 15614-1; Hardness <= 380HV10 | | | |
| **Sample 4** | | | | |
| **Hardness test lf.** | **$d_{\text{Measured value}}$** | **$d_{is}$** | **$d_{is}^2$** | **HV** |
| **1 GW** | 44,8 | 0,32 | 0,10 | **181,1** |
| **2 GW** | 44,2 | 0,32 | 0,10 | **186,0** |
| **3 GW** | 44,9 | 0,32 | 0,10 | **180,3** |
| **4 HAZ** | 43,4 | 0,31 | 0,10 | **193,0** |
| **5 HAZ** | 43,2 | 0,31 | 0,10 | **194,8** |
| **6 HAZ** | 42,9 | 0,31 | 0,09 | **197,5** |
| **7 SG** | 42,8 | 0,31 | 0,09 | **198,4** |
| **8 SG** | 42,6 | 0,30 | 0,09 | **200,3** |
| **9 SG** | 42,7 | 0,31 | 0,09 | **199,3** |
| **10 HAZ** | 42,7 | 0,31 | 0,09 | **199,3** |
| **11 HAZ** | 42,9 | 0,31 | 0,09 | **197,5** |
| **12 HAZ** | 43,1 | 0,31 | 0,09 | **195,7** |
| **13 GW** | 44,6 | 0,32 | 0,10 | **182.9** |
| **14 GW** | 44,9 | 0,32 | 0,10 | **18 1.5** |
| **15 GW** | 44,7 | 0,32 | 0,10 | **182.0** |
| GW: Base material | | | | |
| SG: weld metal | | | | |
| HAZ: Heat affected zone | | | | |
| **Assessment** | **fulfilled** | | | |

## Appendix C

### Test results of the hardness test

| | | | | |
|---|---|---|---|---|
| **Vickers hardness test** | | | **DIN EN ISO 9015-1** | |
| | | | **DIN EN ISO 6507-1** | |
| **Testing machine** | Schenck Trebel Hardness Tester 38532, MPA NRW 43 0453 21- | | | |
| **Test load F** | 98,065 | [N] | | |
| **Request:** | DIN EN ISO 15614-1; Hardness <= 380HV10 | | | |
| **Sample 5** | | | | |
| **Hardness test lf.** | **$d_{\text{Measured value}}$** | **$d_{is}$** | **$d_{is}^2$** | **HV** |
| **1 GW** | 44,7 | 0,32 | 0,10 | **181,9** |
| **2 GW** | 44,5 | 0,32 | 0,10 | **183,5** |
| **3 GW** | 44,6 | 0,32 | 0,10 | **182,7** |
| **4 HAZ** | 42,2 | 0,30 | 0,09 | **204,1** |
| **5 HAZ** | 41,8 | 0,30 | 0,09 | **208,0** |
| **6 HAZ** | 41,5 | 0,30 | 0,09 | **211,0** |
| **7 SG** | 42,5 | 0,30 | 0,09 | **201,2** |
| **8 SG** | 42,9 | 0,31 | 0,09 | **197,5** |
| **9 SG** | 42,6 | 0,30 | 0,09 | **200,3** |
| **10 HAZ** | 41,3 | 0,30 | 0,09 | **213,1** |
| **11 HAZ** | 41,8 | 0,30 | 0,09 | **208,0** |
| **12 HAZ** | 42,1 | 0,30 | 0,09 | **205,1** |
| **13 GW** | 44,5 | 0,32 | 0,10 | **18 2.7** |
| **14 GW** | 44,7 | 0,32 | 0,10 | **181.4** |
| **15 GW** | 44,3 | 0,32 | 0,10 | **183.1** |
| GW: Base material | | | | |
| SG: weld metal | | | | |
| HAZ: Heat affected zone | | | | |
| **Assessment** | **fulfilled** | | | |

## Appendix C

### Test results of the hardness test

| | | | | |
|---|---|---|---|---|
| **Vickers hardness test** | | | **DIN EN ISO 9015-1** | |
| | | | **DIN EN ISO 6507-1** | |
| **Testing machine** | Schenck Trebel Hardness Tester 38532, MPA NRW 43 0453 21- | | | |
| **Test load F** | 98,065 | [N] | | |
| **Request:** | DIN EN ISO 15614-1; Hardness <= 380HV10 | | | |
| **Sample 6** | | | | |
| **Hardness test lf.** | **d** $_{\text{Measured value}}$ | **d** $_{\text{is}}$ | **d** $_{\text{is}}^{2}$ | **HV** |
| **1 GW** | 44,9 | 0,32 | 0,10 | **180,3** |
| **2 GW** | 44,2 | 0,32 | 0,10 | **186,0** |
| **3 GW** | 44,5 | 0,32 | 0,10 | **183,5** |
| **4 HAZ** | 41,5 | 0,30 | 0,09 | **211,0** |
| **5 HAZ** | 41,2 | 0,29 | 0,09 | **214,1** |
| **6 HAZ** | 41,0 | 0,29 | 0,09 | **216,2** |
| **7 SG** | 42,9 | 0,31 | 0,09 | **197,5** |
| **8 SG** | 42,1 | 0,30 | 0,09 | **205,1** |
| **9 SG** | 42,5 | 0,30 | 0,09 | **201,2** |
| **10 HAZ** | 40,5 | 0,29 | 0,08 | **221,6** |
| **11 HAZ** | 40,8 | 0,29 | 0,08 | **218,3** |
| **12 HAZ** | 40,9 | 0,29 | 0,09 | **217,3** |
| **13 GW** | 44,5 | 0,32 | 0,10 | **18 2.2** |
| **14 GW** | 44,7 | 0,32 | 0,10 | **18 2.1** |
| **15 GW** | 44,3 | 0,32 | 0,10 | **18 2.8** |
| GW: Base material | | | | |
| SG: weld metal | | | | |
| HAZ: Heat affected zone | | | | |
| **Assessment** | **fulfilled** | | | |

## Appendix C

### Test results of the hardness test

| | | | | |
|---|---|---|---|---|
| **Vickers hardness test** | | | **DIN EN ISO 9015-1** | |
| | | | **DIN EN ISO 6507-1** | |
| **Testing machine** | Schenck Trebel Hardness Tester 38532, MPA NRW 43 0453 21-8 | | | |
| **Test load F** | 98,065 | [N] | | |
| **Request:** | DIN EN ISO 15614-1; Hardness <= 380HV10 | | | |
| **Sample 7** | | | | |
| **Hardness test lf. N** | **d** **Measured value** | **d** **is** | **d** **is²** | **HV** |
| **1 GW** | 44,6 | 0,32 | 0,10 | **182,7** |
| **2 GW** | 44,7 | 0,32 | 0,10 | **181,9** |
| **3 GW** | 44,5 | 0,32 | 0,10 | **183,5** |
| **4 HAZ** | 41,2 | 0,29 | 0,09 | **214,1** |
| **5 HAZ** | 40,8 | 0,29 | 0,08 | **218,3** |
| **6 HAZ** | 40,1 | 0,29 | 0,08 | **226,0** |
| **7 SG** | 42,5 | 0,30 | 0,09 | **201,2** |
| **8 SG** | 42,6 | 0,30 | 0,09 | **200,3** |
| **9 SG** | 42,2 | 0,30 | 0,09 | **204,1** |
| **10 HAZ** | 39,6 | 0,28 | 0,08 | **231,8** |
| **11 HAZ** | 39,8 | 0,28 | 0,08 | **229,5** |
| **12 HAZ** | 40,1 | 0,29 | 0,08 | **226,0** |
| **13 GW** | 44,9 | 0,32 | 0,10 | **18 2.7** |
| **14 GW** | 44,7 | 0,32 | 0,10 | **18 2.9** |
| **15 GW** | 44,5 | 0,32 | 0,10 | **18 2.3** |
| GW: Base material | | | | |
| SG: weld metal | | | | |
| HAZ: Heat affected zone | | | | |
| **Assessment** | **fulfilled** | | | |

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[8] DIN EN ISO 3452-1:2022-02
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[11] DIN EN ISO 6507-1:2018-07
Metallic materials - Vickers hardness test - Part 1: Test methods

[12] DIN EN ISO 5817:2014-06
Welding - Fusion welded joints on steel, nickel, titanium and their alloys (excluding beam welding) - Evaluation groups of irregularities

[13] https://erl-gmbh.de/fachwissen/schweissdatenrechner/abkuehlzeit-t8-5

## 9. List of abbreviations

| | | |
|---|---|---|
| -t8/5: | cooling time from 800°C to 500°C | [s] |
| -T0 | Preheating temperature | [°C] |
| -Q | Warm insert | [kJ/mm] |
| -F2 | seam factor for two-dimensional heat dissipation | [dimensionless] |
| -F3 | seam factor at threedimensional heat dissipation | [dimensionless] |
| -d | thickness | [mm] |
| -E | plug-in energy | [kJ/mm] |
| -U | electrical voltage | [V] |
| -I | electric current | [A] |
| -$v_w$ | Welding speed | [cm/min] |
| -η | thermal efficiency | [dimensionless] |
| -dü | transition plate thickness | [mm] |
| -ρ | Density | [kg/dm$^3$] |