TECHNICAL TRANSACTIONS 1/2019
MECHANICS
DOI: 10.4467/2353737XCT.19.011.10051
SUBMISSION OF THE FINAL VERSION: 21/12/2018

Hubert Danielewski orcid.org/0000-0003-4675-6236
hubert_danielewski@o2.pl
Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology

Laser welding of pipe stubs made from super 304 steel. Numerical simulation and weld properties

Spawanie laserowe króćców rurowych ze stali super 304. Symulacje numeryczne oraz właściwości złącza spawanego

Abstract

The laser welding process of test pipe stubs which were made from Super 304 stainless steel is usually used to produce components of a power infrastructure. It was numerically simulated and the obtained results are presented in this paper. For the laser welding method, the weldability of this steel is presented, as well as the results of strength and microstructure tests of a joint welded at the parameter settings selected from a numerical simulation. The chemical composition, including the increased content of alloying elements such as chromium and nickel, improves the strength characteristics of the welded steel, allowing for the production of components of superheaters and partition walls of boilers operating in supercritical parameters.

Keywords: laser welding, Super 304 austenitic steel, numerical simulation, SimufactWelding, properties of laser welded joints

Streszczenie

Artykuł przedstawia wyniki symulacji numerycznej procesu spawania laserowego króćców próbnych z nierdzewnej stali kotłowej Super 304 przeznaczonej do wykonywanie komponentów instalacji energetycznych. Przedstawiono spawalność stali z zastosowaniem metody spawanie laserowego, a także wyniki badań wytrzymałościowych oraz mikrostruktury złącza spawanego wykonanego na podstawie parametrów dobranych w symulacji numerycznej. Skład chemiczny, a w tym zwiększona zawartość pierwiastków stopowych, takich jak chrom i nikiel poprawia charakterystyki wytrzymałościowe spawanej stali, umożliwiając wykonywanie z niej komponentów przegrzewaczy oraz ścian działowych kotłów pracujących w parametrach nadkrytycznych.

Słowa kluczowe: spawanie laserowe, austenityczna stal nierdzewna Super 304, symulacje numeryczne, SimufactWelding, właściwości wytrzymałościowe złączy spawanych laserowo

1. Introduction

Recently, in power plants and chemical and petrochemical industries, the use of new high-alloy steels such as Super 304 is considered. Due to the high corrosion resistance and creep resistance of these types of materials in structural applications, their weldability and new welding technology are being developed. The content of chromium and nickel alloys improves anti-corrosion parameters, which extends the operating time of welded elements [1–3].

Although Super 304 austenitic stainless steel is characterized as being well weldable, the laser beam welding (LBW) requires a careful control of a welding temperature [4] and obtaining a proper weld without welding defects is difficult to achieve. Conventional welding methods require the preparation of joining edges by chamfering [5]. Due to the narrowness of the fusion zone, proper fitting of joining edges is required (Fig. 1). The acceptable range of parameters, required to weld a material, could be estimated by using a numerical simulation with a dedicated welding process solver. The paper presents the results of a LBW-based joining method of Super 304 steel, a numerical simulation of the process and the obtained results of welded joint tests.

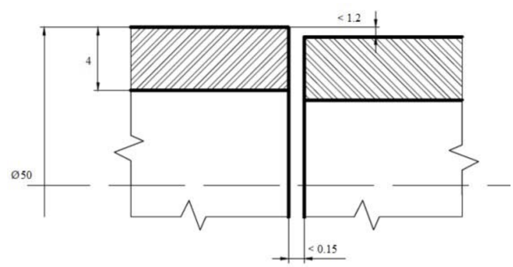

Fig. 1. Preparation of Super 304 pipes edges for laser welding

The Super 304 steel has been developed to replace the currently used 304 steel, which has good weldability due to a high content of chromium and nickel, but has a tendency for porosity at unfavorable operating parameters. The development of new generation materials, such as Super 304, as well as new welding technologies supported by a numerical simulation of the welding process, have contributed to numerous studies [6–8].

2. Material characteristics of Super 304 steel

High temperature resistance characteristic of Super 304 steel is caused by a high content of chromium and nickel elements (Tab. 1), which improves creep resistance. The 18% chromium content increases corrosion resistance and hardenability of the alloy. Niobium is another alloying element that improves creep resistance as well as hardenability. The low carbon content improves the weldability of Super 304 steel, while reducing the risk of hydrogen cracking. In turn, the occurrence of alloying elements, such as copper and manganese, improves the overall strength, and in particular fracture toughness [9].

Table 1. Chemical composition of Super304 steel

Element	C	Si	Mn	Ni	Cr	Cu	Nb	N
Content [%]	0.1	0.3	1.0	9.5	18.0	3.0	0.5	0.09

The traditional method of welding requires the use of an additional material, while the laser welding process is much faster, gives a narrow weld by melting the edge of the material, which also creates a narrow heat affected zone and therefore this process does not require any additional heat treatment.

3. Laser welding of Super 304 steel pipe stubs – numerical simulation

A numerical simulation of the welding process is a complex issue. The obtained computational results are only an estimation of actual test observations. An effective modeling of the welding process requires the use of many simplifications of physical phenomena which occur during welding. The SimufactWelding program uses the method of volumetric heat sources. The volume of a laser beam takes the melting point of a material. The energy fraction associated with the cylindrical heat source describes the energy fraction that will be carried out through a cylinder (Fig. 2), while the remaining energy – through surface heat sources. The parameters of a laser welding process assumed in the numerical simulation are shown in Tab. 2.

Table 2. Settings of heat source parameters assumed in the numerical simulation

Heat source parameters	Power [W]	Velocity [m/s]	Efficiency
Value	4000	0.03	0.8

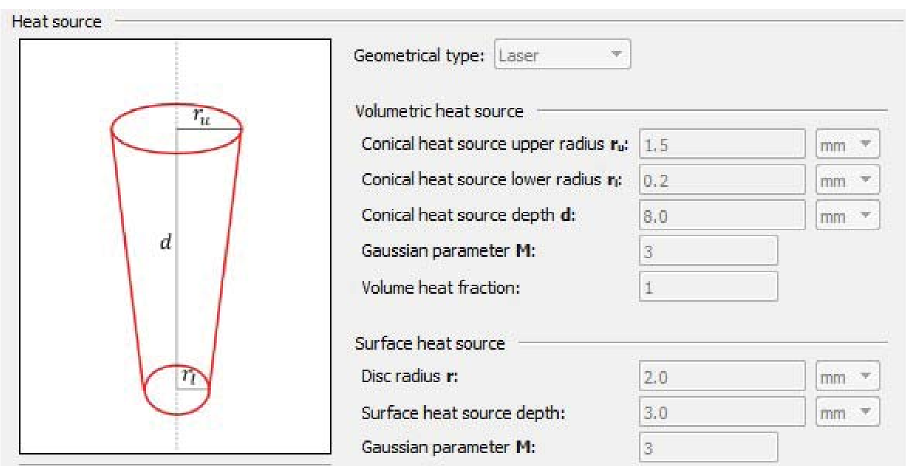

Fig. 2. Programmed volumetric heat sources geometry parameters

The simulated temperature distribution (Fig. 3) showed a correct form of the weld with the material melting through the entire thickness of the pipe. Obtained in the numerical simulation, the predicted shape of the weld shows that the parameters assumed for this simulation should be appropriate for a real laser welding of test pipe stubs made of Super 304 steel.

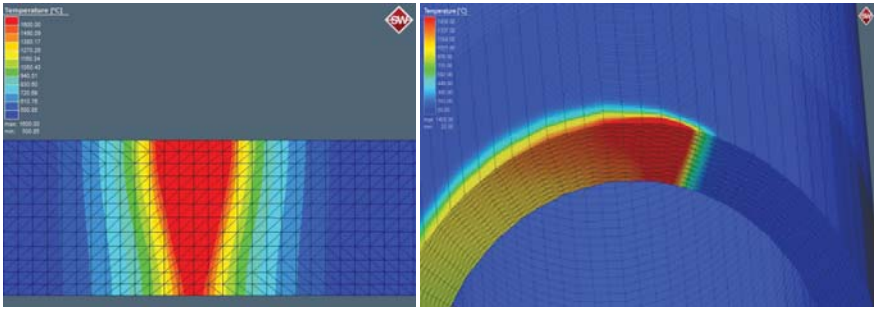

Fig. 3. The simulation of the temperature distribution in the cross and longitudinal section of laser welds

4. Laser welding of Super 304 steel stubs

A circumferential laser welding of pipes made from Super 304 steel with a thickness of 4mm, outer diameter of 50 mm and length of 150 mm was done at settings of parameters shown in Tab. 3.

Table 3. Welding parameters of Super304 steel pipes joints

Heat source parameters	Power [W]	Velocity [m/s]	Frequency [kHz]
Value	4000	0.03	50

The welding device used was a high power CO_2 laser Trumpf TruFlow 6000 with the maximum power of 6 kW mounted on the additional rotary axis of a TruLaser Cell 1005 work center. A welding head with a focal length of 200 mm was used. The pipes were fixed on a rotary axis. Inside the pipes, due to the protection of a weld root, shielding gas (argon with the efficient of 12 l/min) was conveyed. Due to the highest ionization potential, helium with coaxial-blown of 20 l/min was used to protect the face of the weld. The obtained results of weld tests refer to joints without a post-weld treatment [10, 11].

5. Non-destructive tests

The most frequently observed welding defects that may occur during a circumferential laser welding are incomplete welds, groove contraction, porosity (Fig. 5) or poor connection. The evaluation of weld quality requires several tests of welding methods. The results of visual tests (VT) and ultrasonic tests (UT) of welds are presented below.

Visual testing was conducted according to PN-EN ISO 17637 [12]. The acceptable quality level was identified according to PN-EN ISO 13919-1 [13]. The weld qualified to B quality level (stringent requirements) is shown in Fig. 4.

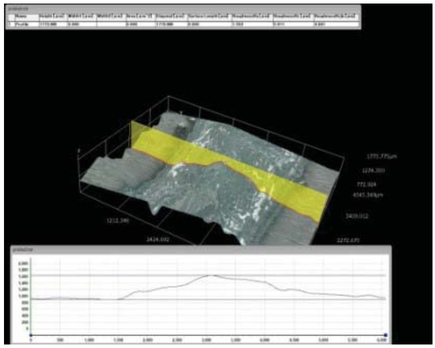

Fig. 4. Visual testing of a weld's face surface geometry for Super 304 steel

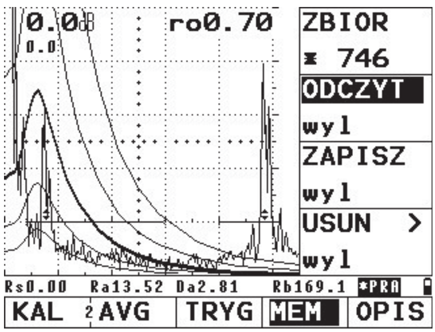

Fig. 5. Ultrasonic tests result – detection of gas pore inside weld

In the performed test, an ultrasonic flaw detector USM 35S of GE (Krautkramer) industry was used. The echo-sounding method was applied by front (MSEB-4) and side (MWB 70 4) measuring head using the DGS (DDSR = 0.7 mm) scale. A typical ultrasonic-based detection of a gas pore is shown in Fig. 5. The defect was recognized as the lack of the side fusion on the side of the weld edge, which might have been caused by a faulty crystallization process as well as a gas pore defect.

6. Destructive tests of welded joints

The austenitic structure and alloy elements increase the strength characteristics of Super 304 steel and, in addition, a reduction of the heat affected zone in the base material was obtained by using laser welding with optimized parameters selected by a numerical simulation. It should be noted that the strength characteristics of a weld are of decisive importance in determining the acceptance level of welded joints.

When considering the durability and safety of welded gas or boiler installations, it is important to ensure that the welded material and the heat affected zone (HAZ) have properties similar to the basic material (BM). To examine the quality of welded joints obtained without a post-heating treatment, the microhardness testing in cross-section was done. The hardness test was carried out in accordance with PN-EN ISO 6507-1 [14]. Fig. 7 shows the results of microhardness of the weld cross-section.

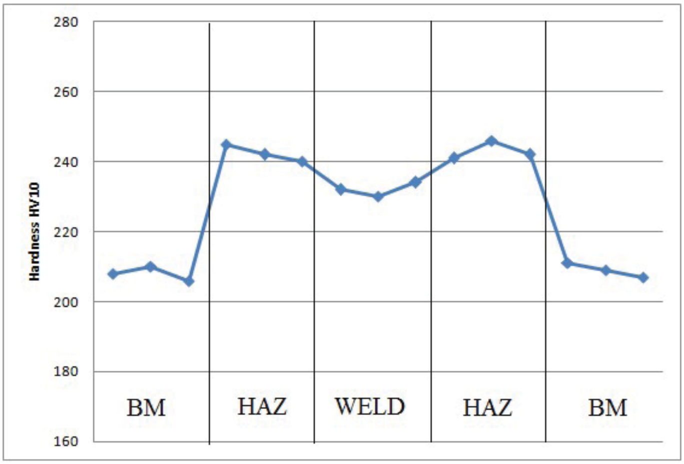

Fig. 6. The microhardness distribution in the weld cross-section

The results of the hardness test show an increase in the weld and HAZ. The hardness distribution is typical for the laser welding, with stronger reinforcement in the heat affected zone and slightly lower in the welding zone. According to PN-EN ISO 15614-11, the maximum allowable hardness limit for Vickers HV10 is 350 [15]. The obtained results do not exceed the value of 350 HV10 (maximum measured value – 247 HV10), so the obtained weld does not require any additional heat treatment.

7. Metallographic test

A metallographic study was carried out in accordance with PN-EN ISO 17639 [16]. Microscopic and macroscopic examinations were performed using a Hirox KH-8700 digital confocal microscope. The macrostructure was shown at a magnification of 35x (Fig. 8) and the microstructure with a magnification of 600x (Fig. 9). The macroscopic image of the weld cross-section shows properly formed joints. At the edge of the weld, a gas pore is visible, which was detected in the ultrasonic test.

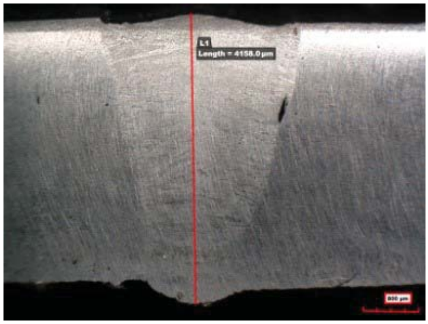

Fig. 7. Macrostructure of weld (Hirox confocal digital microscope, magnification 35x)

The obtained weld joints are characterized by the lack of welding defects except for a small pore of gas. Typical BM, HAZ and weld microstructures images for Super 304 austenitic stainless steel weld are shown in Fig. 9. The typical final weld structure of Super 304 steel is austenitic.

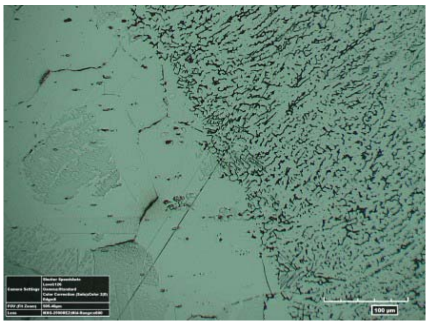

Fig. 8. Microstructure of weld (Hirox KH-8700 with magnification of 600x)

8. Conclusions

A study of laser welded pipe stubs was carried out. According to PN-EN ISO 13919-1 standard [13], stringent requirements of B quality level were obtained. Destructive and nondestructive tests confirmed proper strength characteristics and correct cross-section welds construction. According to PN-EN ISO 15614-11 standard [15], due to the obtained hardness values which do not exceed the limit of 350 HV10, post-weld treatment for joints welded by a laser is not required. The numerical simulation gave results similar to the real tests with samples welded by a laser.

The research was carried out in the NCBiR project of National Centre for Research and Development (NCBiR) No. LIDER/31/0173/L-8/16/NCBR/2017 „Technology of manufacturing sealed weld joints for gas installation by using concentrated energy source".

References

[1] Viklund P., Hjörnhede A., Henderson P., Stålenheim A., Pettersson R., *Corrosion of superheater materials in a waste-to-energy plant,* "Fuel Processing Technology", Vol. 105/2013, 106–112.

[2] De Oliveira M.P., Zhang W., Yu H., Bao H., Xie X., *Recent developments in niobium containing austenitic stainless steels for thermal power plants,* [in:] Conf. Energy Materials 2014, Xi'an Shaanxi Province, China, 2014, 271–277.

[3] Koscielniak B., Smola G., Grzesik Z., Hernas A., *Oxidation resistance of austenitic steels under thermal shock conditions in an environment containing water vapor,* "High Temperature Materials and Processes", Vol. 73(4)/2018, DOI: 10.1515/htmp-2016-0209 (access).

[4] Danielewski H., Skrzypczyk A., Antoszewski B., Zowczak W., Zrak A., *Microstructures and properties of laser welded Super304 steel pipe joints using LNM304 filler wire as an additional material,* Proc. SPIE, Vol. 10974/2018, art.109740P.

[5] Scendo M., Radek N., Trela J., *Influence of laser treatment on the corrosive resistance of WC-Cu electrospark coatings,* "International Journal of Electrochemical Science", Vol. 8/2013, 9264–9277.

[6] Radek N., Konstanty J., *Cermet ESD coatings modified by laser treatment,* "Archives of Metallurgy and Materials", Vol. 57/2012, 665–670.

[7] Klimpel A., *Technologie laserowe. Spawanie, napawanie, stopowanie, obróbka cieplna i cięcie,* Wyd. Politechniki Śląskiej, Gliwice 2012.

[8] Gątarek, M., Słania J., Rawicki Ł., Golański G., Krawczyk R., Urbańczyk P., *Spawanie złączy doczołowych jednorodnych ze stali Super 304H,* „Przegląd Spawalniczy", Vol. 88(4)/2016, 31–34.

[9] Zbroja P., Ziewiec A., Tasak E., *Skłonność do pęknięć gorących austenitycznej stali Super 304H przeznaczonej do pracy w podwyższonej temperaturze,* "Przegląd Spawalniczy", Vol. 84(1)/2012, 10–14.

[10] Słania J., Urbańczyk P., *Technologia wytwarzania oraz plan kontroli jakości przegrzewacza pary kotła parowego wg PN-EN 12952-5,* "Przegląd Spawalnictwa", Vol. 5/2012, 29–41.

[11] Skrzypczyk A., Danielewski H., *Properties and Microstructure of Laser Welded VM12-SHC Steel Pipes Joints,* "Archives of Metallurgy and Materials", Vol. 61(2B)/2016, 1143–1149.

[12] PN-EN ISO 17637:2011 – Badania nieniszczące złączy spawanych – Badania wizualne złączy.

[13] PN-EN ISO 13919-1:2002 Spawanie – Złącza spawane wiązką elektronów i wiązką promieniowania laserowego – Wytyczne do określania poziomów jakości według niezgodności spawalniczych.

[14] PN-EN ISO 6507-1:2007 Metale – Pomiar twardości sposobem Vickersa – Część 1: Metoda badań.

[15] PN-EN ISO 15614-11:2005 Specyfikacja i kwalifikowanie technologii spawania metali. Badanie technologii spawania. Część 11: Spawanie wiązką elektronów i wiązką promieniowania laserowego.
[16] PN-EN ISO 17639:2013 Badania niszczące spawanych złączy metali – Badania makroskopowe i mikroskopowe złączy spawanych.

If you want to quote this article, its proper bibliographic entry is as follow: Danielewski H., *Laser welding of pipe stubs made from super 304 steel. Numerical simulation and weld properties*, Technical Transactions, Vol. 1/2019, pp. 167–176.