BY-NC

Hubert Danielewski, Andrzej Skrzypczyk, Włodzimierz Zowczak, Piotr Furmańczyk, Dariusz Gontarski

Numerical Modelling of the Bifocal Laser Welding of Unalloyed Structural Steels

Abstract: The article presents the possibilities of the numerical modelling of laser welding processes. In laser welding, the concentrated beam of photons generates high surface power density and leads to the melting and even evaporation of some metal. The metal vapours ionize and form a keyhole. Because of its high linear power density, laser welding process makes it possible to form deep and narrow welds. However, this welding method requires the preparation of workpiece edges. It is possible to "bypass" this requirement by defocusing the laser beam. However, the foregoing entails a significant decrease in power density. An alternative involves the use of optical systems enabling the division of the beam. In CO_2 gas lasers, the bisection of the laser beam is performed using a multi-faceted parabolic mirror. The modelling of welding processes can be carried out using both analytical and numerical methods. Analytical solutions provide approximate results and do not take into consideration many physical phenomena accompanying welding processes. In turn, numerical solutions provide a more accurate representation of welding processes, In addition, it is possible to modify the geometry of heat sources reflecting the keyhole effect of bifocal welding system. The paper presents results of the numerical simulation of the keyhole laser welding process in relation to a bifocal optical system. The results of the numerical simulation were verified experimentally by making test joints using parameters developed during numerical simulations. Both the shape of obtained welds and the hardness distribution identified in the cross-section of a joint made of low-alloy structural steel S235JR were subjected to tests in order to verify the numerical model.

Keywords: laser welding, numerical simulation, bifocal welding, welding of low-alloy steel S235JR

DOI: *10.17729/ebis.2019.6/6*

Hubert Danielewski, MSc Eng.; Andrzej Skrzypczyk, PhD (DSc) Eng.; Włodzimierz Zowczak, PhD (DSc) Habilitated Eng., Professor at PŚk /Kielce University of Technology/, Piotr Furmańczyk, MSc Eng.; Dariusz Gontarski, PhD (DSc) Eng. – Wydział Mechatroniki i Budowy Maszyn, Politechnika Świętokrzyska /Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology/

BY-NC

Characteristics of bifocal laser welding

Welding processes are widely used when making permanent joints. Conventional welding methods applied in industrial conditions usually utilise electric arc as the source of heat [1]. Welding methods also include unconventional methods, i.e. where the source of heat is the beam of energy, (e.g. beam of electrons), ionised plasma or the beam of photons (as is the case with laser welding). An unquestionable advantage of laser welding is very high power density obtained by the focusing of the laser beam. As a result, it is possible to conduct the welding process at a significant rate, leading to the formation of a very narrow heat affected zone and only slight welding distortions. In terms of keyhole welding, i.e. where the surface power density of the focused beam exceeds 10^6 w/cm^2, ionised metal vapours form a deep cylindrical keyhole, which, once the welding power source has been removed, cools down to form a weld.

A very narrow laser beam-affected zone is undoubtedly one of the most important advantages of the above-named method, yet it also necessitates the very precise preparation of edges of elements to be welded. The heat affected zone can be extended by defocusing the beam, which, however, entails a decrease in power density and, consequently, deterioration of welding process efficiency. Metallic surfaces are characterised by significant reflexivity as regards laser radiation at the first stage of the process, yet, along with an increase in temperature, the absorption of the laser beam grows and enables the performance of the welding process. The extension of the heat affected zone without the necessity of reducing surface power density can be achieved through the bisection or division of the beam and focusing the resultant beams close to one another on the material surface. Depending on a given laser type, the division of the beam can be obtained by using a lenticular-prismatic systems or multi-faceted parabolic mirrors (see Figure 1).

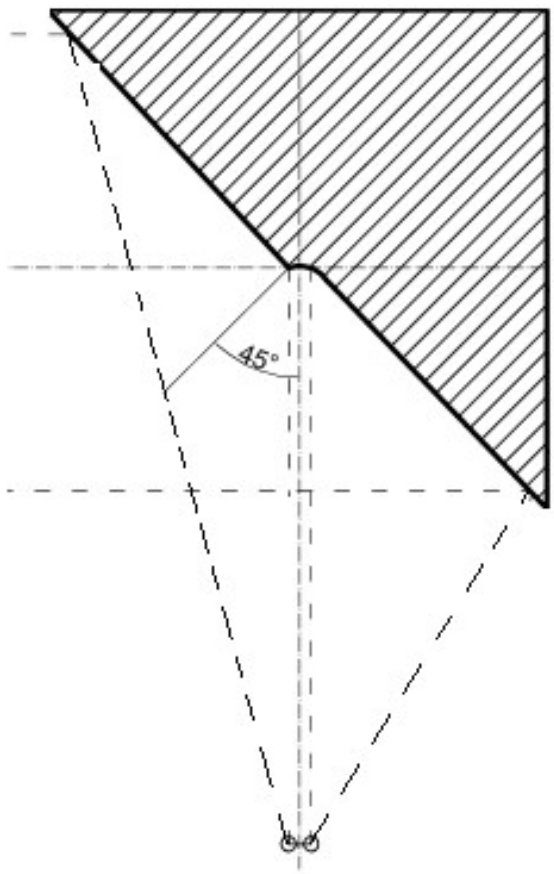


Fig. 1. Bifaceted focusing mirror

The use of bifocal systems enables the extension of the zone affected by the laser beam without significant losses of a heat input to a material subjected to welding. The application of systems with mirror-based focusing enables the performance of welding using two focus positioning configurations [2–3].

Numerical simulation of laser welding

Welding technologies are used when making joints of various metallic materials including structural steels, alloy steels, superalloys or other types of metals such as, e.g. titanium. Each type of material is characterised by specific thermophysical properties affecting its weldability and the course of the welding process itself. In many cases, the assessment of weldability and the adjustment of welding parameters prove laborious and costly. Because of this, the past seventy years have seen the application of analytical methods enabling the assessment of thermal cycles and temperature fields during welding. However, the above-named methods do not take into consideration many

BY-NC

physical phenomena accompanying the process of welding. The analytical method-aided design of welding processes evolved through the application of FEM-based numerical methods. Technological development combined with higher computational power made it possible to solve systems of integral equations providing more accurate solutions [4].

Software programmes for the numerical simulation of welding processes include advanced programmes describing thermophysical phenomena e.g. ANSYS-Fluent, which, if properly programmed, provide very precise results, However, the time required for the performance of related calculations is long. Other software programmes, such as Sysweld SimufactWelding, dedicated to welding processes, are based on simplified algorithms of calculations. In the study discussed in the article, the software programme used to simulate a welding process was SimufactWelding [5].

Numerical model of bifocal laser welding

At the first stage, the modelling of welding processes involves the definition of welding power source geometry. In terms of laser welding, the Simufact software programme offers a cylindrical welding power source which is conical in cross-section and simulates the operation of a keyhole inside a material. The keyhole depends on a focusing system "currently" in use. Figure 2 presents the adopted dimensions of the cylindrical heat source.

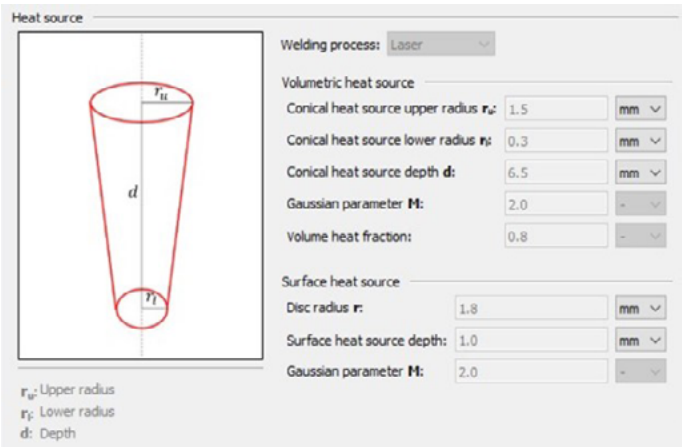


Fig. 2. Screenshot of the software programme with dimensions of a cylindrical heat source

The subsequent stage involves creating the geometry of the solid of an object to be welded, defining appropriate restraints in space and dividing the solid into finite elements. In terms of welding performed using bifocal systems, the size of finite elements must be the multiple of the distance between the focuses of the system. The foregoing is a precondition making it possible to programme the movement of both beams. Afterwards, it is necessary to define the trajectory along which the programmed welding power sources will move. The simulation of the effect of the bifocal system was performed using two independent and simultaneous processes, where the geometries of individual welding power sources overlap creating the bifocal system (Fig. 3).

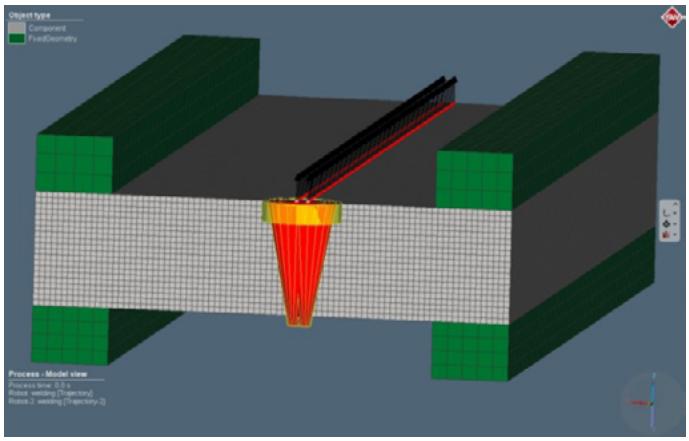


Fig. 3. Numerical model of bifocal laser welding

Numerical simulation results

The simulation of the laser welding process was performed in relation to two configurations of the beam focusing system, i.e. single beam laser welding and bifocal laser welding, where welding power sources moved side by side. During the simulation, attention was paid to the effect of a welding rate range on the shape of penetration. A laser radiation source output power of 6 kW was set as a constant parameter. In relation to the simulation based on moving welding power sources, the parameter of laser impulse frequency is ignored. Simulations were performed in relation to welding rates restricted within the range of 3 m/min to 1 m/min, with an increment of 0.2 m/min. The base material

BY-NC

used in the tests was steel grade S235JR, i.e. in relation to which the SimufactWelding software programme has complete libraries with variable thermophysical parameters and the table of phase transformations of the material, thus enabling the performance of entire thermophysical analysis. In relation to the bifocal system it was necessary to adjust the bisection of power, amounting to 3 kW in relation to each of the beams. The adopted thermal efficiency amounted to 0.9 in relation to the Gaussian parameter describing the distribution of radiation intensity in a cross-section of 3. The numerical simulation results related to a welding rate of 3 m/min are presented in Figure 4.

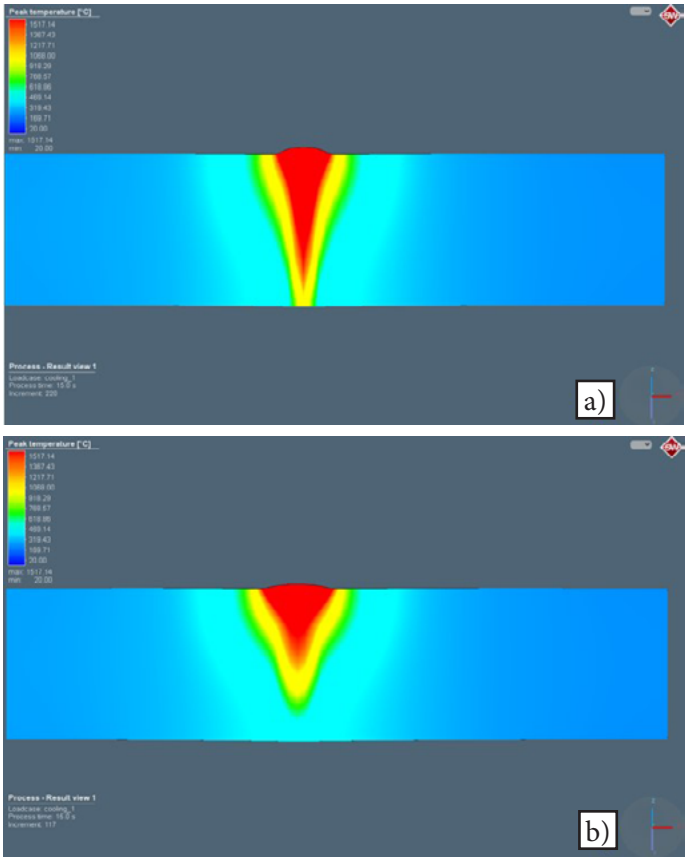


Fig. 4. Weld shape in cross-section in relation to the unifocal (a) and bifocal system (b)

Numerical analyses were performed using the same parameters in both simulation variants, where, in the case of the bifocal system, the output power was the total power of both beams, the focal lengths of which were located 0.7 mm away from each other. Numerical simulations were performed for the entire range of adopted welding rates until the obtainment of the proper structure of the weld in relation to both welding variants. In relation to the unifocal variant, full penetration (g = 6 mm) was obtained at a welding rate of 1.4 m/min. However, to compare the shapes of the welds in crops-section, the simulation was performed in relation to a rate of 1.2 m/min in both cases. The results of the simulation are presented in Figure 5.

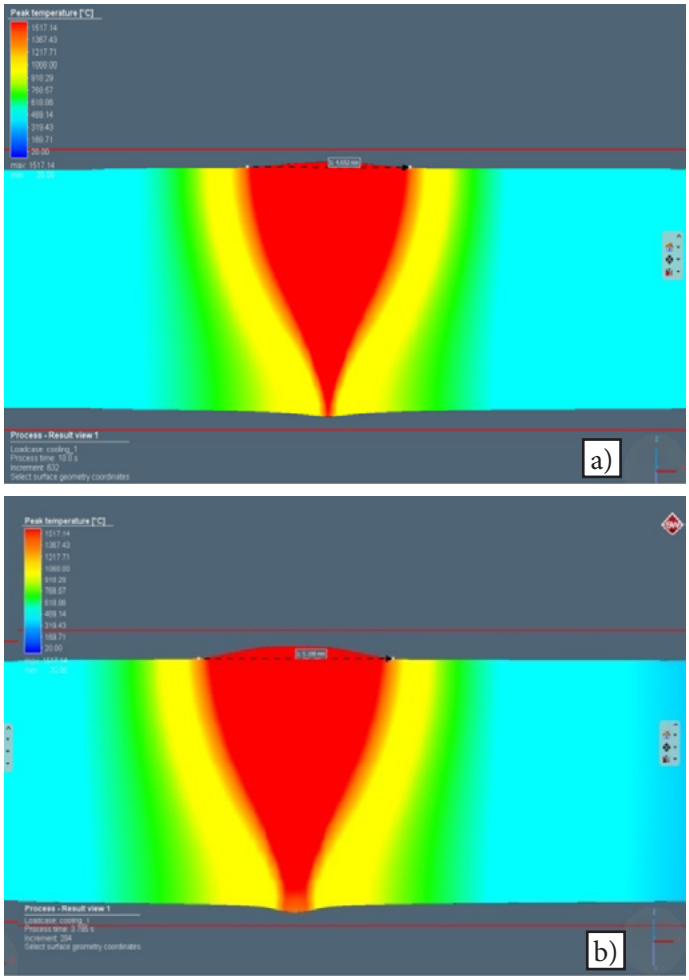


Fig. 5. Weld shape in relation to the unifocal (a) and bifocal system (b) and a welding rate of 1.2

In relation to the unifocal system, the weld face width amounted to 4.5 mm. In turn, in relation to the bifocal system, the weld face width amounted to 5.2 mm. As can be seen in Figure 5, also the width of the weld root is significantly greater in relation to the bifocal variant. In relation to the bifocal variant, full penetration was obtained at a welding rate lower by 0.2 m/min than that used in relation to the unifocal variant. The foregoing resulted from the depth affected by welding power source and the division of power.

BY-NC

Experimental verification of results obtained in the numerical modelling of laser welding

Test joints

The parameters obtained in the numerical simulation of the laser welding process were used to perform the test melting of a 6 mm thick plate made of steel S235JR. Table 1 presents the chemical composition of the steel.

Table 1. Chemical composition of steel S235JR

Element	Mn	Si	Cu	Cr and Ni	Nb	Mo	B
Content [%]	1.65	0.5	0.4	0.3	0.06	0.08	0.0008

The welding process was performed using a TruLaserCell 1005 station provided with a TruFlow 6000 CO_2 laser having a maximum output power of 6 kW. The parameters used in the process were those determined during simulation, i.e. an output power of 6 kW and a welding rate of 1.2 m/min. The shielding gas used in the process and tasked with limiting the effect of ionisation on the absorption of radiation was helium, fed at a flow rate of 15 l/min. A high frequency of welding impulses of 50 kHz was adopted to obtain the effect of continuous welding. The laser beam was focused on the surface of the material subjected to welding [6] (Fig. 6).

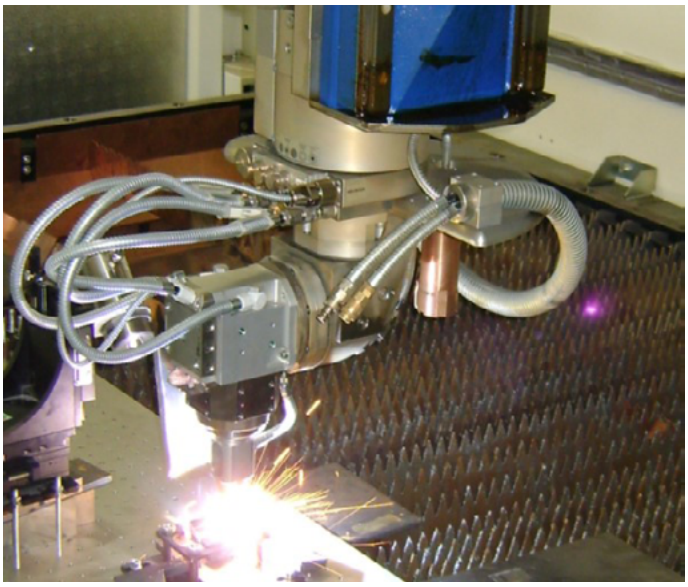


Fig. 6. Laser welding of the test joints made of steel S235JR

Comparative analysis of numerical simulation results with actual test joints

The shape of the weld in cross-section

The most typical welding imperfections formed in laser welding processes include the irregular weld face, undercuts and lacks of penetration. Because of this, the initial assessment of the quality of joints requires the performance of visual tests (VT). The assessment of the weld structure in cross-section was performed using a Hirox KH-8700 confocal digital microscope and a magnification of 35 times. The microscopic analysis revealed the proper structure of the weld, characterised by the convex face and full penetration. Afterwards, the shape of the actual butt weld was compared with that obtained in numerical simulation (Fig. 7).

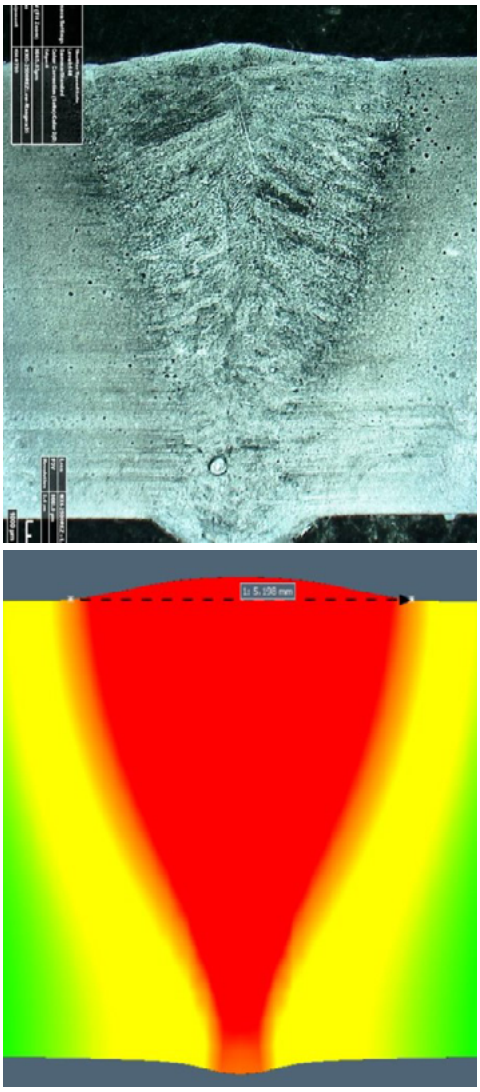


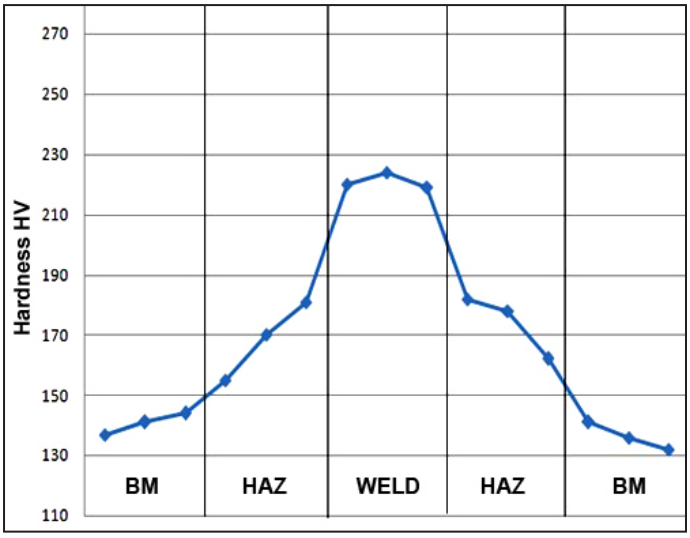
Fig. 7. Cross-sectional shape of the weld in the test joint and computer-aided simulation

BY-NC

Hardness tests

The performance of complete thermophysical analysis including phase transformations of a material subjected to welding also makes it possible to identify selected mechanical properties of the above-named material, including hardness distribution in the cross-section of the joint. Figure 8 presents cross-sectional hardness distribution in relation to the actual joint (b) and obtained in numerical simulation (a).

a)



b)

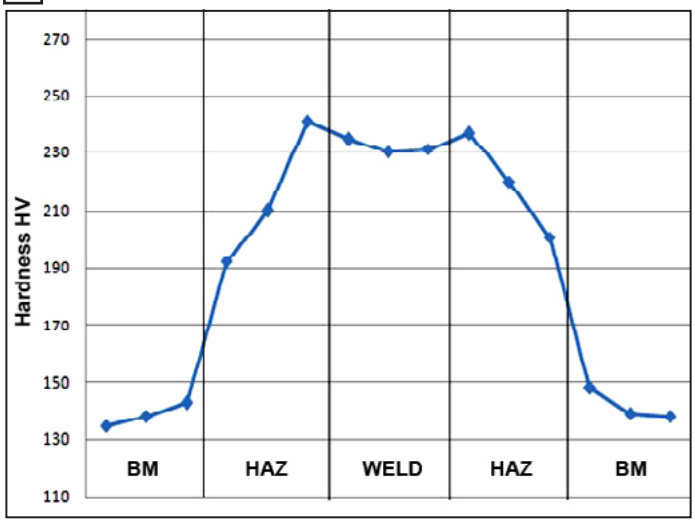


Fig. 8. Hardness distribution in the cross-section of the joint in relation to the numerical simulation (a) and the test joint (b)

Summary

The use of programmes for the simulation of laser welding processes, e.g. SimufactWelding, makes it possible to determine technological welding parameters enabling the obtainment of full penetration, thus significantly reducing the amount of experimental tests. Differences between simulation and experimentation may result from software programme-related limitations, where certain thermophysical phenomena are taken into consideration when calculating welding source power by applying a damping factor. The use of bifocal systems makes it possible to widen the weld in cross-section without significantly increasing a heat input to the material subjected to welding. Further tests, involving the numerical and experimental analysis of stresses and strains accompanying laser welding processes will make it possible to match a numerical model better and obtain the more accurate divergence of results.

The research-related tests were performed within project of the National Centre for Research and Development no. LIDER-/31/0173/L-8/16/NCBR/2017 "Technology of Making Leak-tight Joints in Gas Systems Made Using Concentrated Welding Power Sources".

References

[1] [Pilarczyk J.(red.): Poradnik inżyniera. Spawalnictwo, vol. l. Wydawnictwa Naukowo-Techniczne, Warszawa, 2003.

[2] Skrzypczyk A., Danielewski H.: Properties and Microstructure of Laser Welded VM12-SHC Steel Pipes Joints. Archives of Metallurgy and Materials, 2016, vol. 61, no. 2B, pp. 1143–1149. http://journals.pan.pl/dlibra/publication/106925/edition/92622/content

[3] Kimpel A.: Technologie laserowe. Wydawnictwo Politechniki Śląskiej, Gliwice, 2012.

[4] Steen W.: Laser Material Processing. Springer, London, 2003.

[5] Falk N., Flaviu S., Kümmel B., Bergmann J. P., Hildebrand B: Optimization Strategies for Laser Welding High Alloy Steel Sheets. Physics Procedia, 2014, vol. 56, pp.

BY-NC

1242–1251
https://www.sciencedirect.com/science/article/pii/S1875389214001850?via%3Dihub
[6] Górka J., Ozgowicz A.: Próby spawania laserowego niskostopowej wysokowytrzymałej stali o strukturze martenzytycznej. Przegląd Spawalnictwa, 2016, vol. 88, no. 5, pp. 24–27. http://pspaw.pl/index.php/pspaw/article/view/607