Research Article

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Numerical Simulation of Laser Welding Dissimilar Low Carbon and Austenitic Steel Joint

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Abstract: Numerical simulation of laser welding dissimilar joint was presented. Results of butt joint for low carbon and austenitic steels are studied. Numerical calculations based on thermo-mechanical method and phase transformation were used for estimating weld dimensions and joint properties. Unconventional welding method where focused photons beam are used as a heat source were presented. Problems with welding of dissimilar joints, where different composition and thermo physical material properties affect on this phenomena complexity are solved using numerical methods and laser welding technology. Simulation of low carbon and stainless steel joints using SimufactWelding software are presented. Model of heat source within geometry and parameters was programmed. Laser beam welding simulation was performed for estimating parameters for complete joints penetration. Programming welding boundary condition and heat source geometry welding parameters with output power and welding speed rate was estimated. Materials used in simulation process and experimental welding was low carbon construction S235JR and stainless 316L steels in sheets form. Joint properties such as fusion zone and heat affected zones dimensions and stress-strain distribution were calculated. Estimation of complete joint characteristics was obtained using thermo-mechanical simulation method and Marc solver engine.. Experimental trial butt joint welding were performed based on estimated parameters. Welding process was performed using 6kW CO₂ laser system. Based on numerical simulation, microstructure analysis, hardness distribution and chemical distribution of fusion zone, properties of obtained joint was studied. Model for simu-

lation of dissimilar laser welding joint was obtained, and properties of obtained joint based on simulation and experiment was studied.

Keywords: laser welding, numerical simulation, dissimilar butt joint, austenitic and low carbon steels

1 Introduction

Article present laser welding results of austenitic and low carbon steels joint, where numerical simulation is used for estimating welding parameters and performing joint properties analysis. Properties of obtained butt weld joint are studied based on simulation stress-strain analysis, experimental validation, performed destructive test and metallographic analysis. Therefore possibility of using software dedicated for welding simulation in order to predict parameters of laser dissimilar joint welding was presented, moreover joint properties analysis based on simulation results was presented. Welding of dissimilar material is complex problem, and require consider weldability of two materials with different chemical compositions and thermo physical material properties [1, 2]. Conventional welding methods use filler material and electric arc as a heat source. Nevertheless additional material usually have some differences in chemical compositions compare to welded materials, and may caused some difficulties and extend complexity of joining process. Therefore welding of dissimilar materials using concentrated photons beam, where welding process is performed by melting edges of joined materials and crystallization process can be performed without filler material. Laser beam welding (LBW) with key-hole phenomena, where high surface energy density of focused photons beam, exceeding $2 \cdot 10^6 \text{ W/cm}^2$ allow to obtain deep welding penetration with high speed rate [3, 4]. Nowadays, many researcher studied modern technology, where plasma, laser or electron beams are used as a heat sources for welding of metallic materials [5–7]. Among conducting research, advanced joints of titanium with aluminum alloys [8–10], and similar joints of high alloy mate-

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rials are analyses. Weldability of low carbon with stainless steels are studied widely, however usually steel in grade 304, as well as research over simulation of this joints type. However lots of them are based on conventional welding methods and even consider electron or laser welding, process parameters were selected experimentally or for pulse welding mode [11]. Moreover aided methods based on simulations are carried out with solving complex heat-mass flow equations (ANSYS-Fluent) [12–14]. However some software use simplifying some physics phenomena, where programming are based on macros implementing (SYSWELD) or software dedicated for stress-strain analysis with additional welding module (Abaqus) [15–17]. Nevertheless software base on simple solving engine give less accurate results, and advanced numerical programs require high programming capability. Performing numerical simulation in SimufactWelding software, dedicated for welding applications, where multiphase nonlinear problem using Marc solver was simulated with good time to accuracy factor [18]. Alternative to time consumable numerical simulations are analytical methods, where solving heat transfer in solid material problem fusion zone can be estimated. This methods give quick, however only approximate solution. Numerical methods give simplifying or override some physics phenomena, nevertheless solving nonlinear finite element solution accurate results can be obtained [19]. Therefore in dissimilar joint where materials with different thermo physical material properties are welded numerical methods can be used [20, 21]. Programming welding simulation heat source geometry and properties is crucial, therefore for obtaining accurate results of fusion zone (FZ) and heat affected zone (HAZ) geometries, stress-strain distribution and thermal gradients HS calibration is required [22, 23].

Validation of simulation results are performed based on trial joint, were welding parameters estimated in numerical simulation was used. Laser welding machine used for experimental welding was Trumpf TruFlow 6000 laser source mounted on 6-axies TLC1005 laser machine. Due to reduce heat accumulation in material, laser power for numerical simulation was set as maximum output power of laser system equal to 6kW. Heat source speed rate for obtained complete joint penetration was calculated. Welding trajectory was set on edges of attached S235JR and 316L steels sheet plates meshed using solid finite elements [24, 25].

Thermo physical material properties as absorption of laser beam in metal surface and material conductivity affect on results of dissimilar welding joint properties. Results of welding numerical simulation with properly defined boundary conditions give accurate estimation of weld dimension. Performing complex calculations using

Table 1: Chemical composition of used materials (in wt-%)

Material	C _{max}	Mn _{max}	Mo _{max}	S _{max}	Cu _{max}
S235JR	0.17	1.4	0.045	0.04	0.55
Material	C _{max}	Mn _{max}	Mo _{max}	Ni _{max}	Cr _{max}
316L	0.03	2.0	3.0	14.0	18.0

library of variable material properties thermo-mechanical analysis with phase transformation can be performed [26].

Paper presents study of numerical simulation of dissimilar laser welded butt joint with experimental verification, moreover according to performed simulation, properties of joint was estimated. Therefore further analysis of obtained trial joint was performed, where hardness test, microstructure and electron dispersive spectroscopy analysis was carried out.

2 Numerical simulation

In boundary conditions rigid restraint using fixing geometry was used, and specimen in form of two sheet plate 30x20mm and thickness 6mm simulated welded elements was established. Geometry was meshed using hexahedral type of elements, where general size was programmed as 1mm, however in area near welding trajectory, FE was refine and size was equal to 0.25mm (Figure 1). Simulation process of laser welding uses volumetric heat source based on double cylindrical model. Therefore conical HS (simulated keyhole effect) with upper radius 0.4mm, down radius 0.2mm and depth geometry equal to 12mm, and disc HS (simulated laser absorption effect) with radius 0.5mm and depth 0.2mm was programmed. For programmed geometry materials libraries with variable thermo-mechanical properties of low carbon and stainless steels was assigned. Materials selected for simulation was low carbon ferritic-pearlitic construction steel in grade S235JR and austenitic stainless steel in grade 316L.

SimufactWelding software based on Marc solver for laser welding simulation was used. Laser welding of butt joint use single pass process where heat source moving along attached edges was simulated. Calculation of heat distribution during welding process was performed in order to estimate weld and HAZ dimension. Stress and strain analysis of obtained dissimilar joint was studied.

Numerical simulation of welding process was performed in 7 steps, with constant maximum output power equal to 6kW and speed rate between 800 - 2000 mm/min with step 200 mm/min. Laser welding simulation process

Figure 1: Numerical model of laser welding dissimilar butt joint: a) welding configuration, b) finite element model

Figure 2: Overview of laser welding process of dissimilar butt joint

Figure 3: Dimensions of simulated dissimilar laser welded joint in cross section

was performed according to established boundary conditions (Figure 2).

Welded materials properties affect on heat expansions, therefore some differences in weld pool and HAZ geometries can be shown. Estimation of welding properties was performed based on performed simulations. For first step simulation with maximum output power and 2mm/min speed was carried out, and with every next step was reduced until complete weld penetration were obtained (Figure 3). No preheat or post weld heat treatment was programmed. Laser welding simulation of dissimilar butt joints was performed for constant output power, changed welding speed rate, and HS parameters, where efficiency of 0.9 and Gaussian parameter of conical heat source equal to 3 was programmed. Results of simulation shown that output power equal to 6kW for 6mm S235JR and 316L steel sheets with speed of 1000 mm/min give complete joint penetration.

Results of simulation for speed rate of 1200 mm/min give erratic penetration. Thermo-mechanical simulation give realistic results of welding process with convex face of weld and material deformation. Parameters given from nu-

merical simulation were used in experimental welding process to verifying numerical model. Differences in dimension of weld sides result from used material, chemical composition (Table 1) and thermo physical properties such as thermal conductivity and diffusivity, which affect on melting and solidification process (Table 2).

Table 2: Basic thermo physical properties of welded materials

Material	Thermal conductivity	Specific heat	Thermal expansion	Latent heat
S235JR	47	470	12	250
316L	15	480	16	300

Obtained joint simulation results was used for stress-strain analysis, therefore effective stress and yield stress distributions was studied (Figure 4, 5).

Figure 4 shown effective stress distribution for complete penetration of dissimilar butt joint of low carbon and stainless steel. Greater stress distribution occur in

Figure 4: Effective stress distribution of simulated laser welded joint in cross section

stainless steel. Laser welding process was performed with speed 1m/min and output power equal to 6kW. High temperature gradient combining with differences in thermo physical material properties affect on welding results. Significantly higher value of low carbon steel thermal conductivity result in narrower fusion zone and differences in phase transformation. Solidification of molten metal, chemical composition and thermal gradient define crystallographic structure of welded materials, and affect on stress-strain distributions.

Figure 5: Yield stress distribution of simulated laser welded joint in cross section

Material using in welding simulation are characterized as good weldable, chemical composition and thermo physical material properties affect on differences in stress and displacement in welded materials. Calculated results of full penetration welding process was achieved. Greater value of effective stress (562 MPa) and yield stress (557MPa) occur in stainless steel.

3 Experimental laser welding of trial joint

Estimating parameters based on numerical simulation was used to perform trial joint. Using CO₂ Trumpf TruFlow 6000 laser system with maximum output power equal to 6kW was used. Welding process with speed of 1m/min and output power 6kW was conducted (Figure 6). Numerical simulation do not assume shielding gas effect, therefore to reduce surface tension and ionization effect helium with flow rate 15l/min was used. Two steel sheets with thickness of 6mm was welded using laser beam. Process welding head with focal length of 270mm, and coaxial shielding gas delivery system was used.

Figure 6: Experimental laser welding stand

Trial joint with complete weld penetration and good weld build was obtained. Moreover no defects in form of incompletely filled groove, root concavity, cracks or porosity in visual test (VT) was detected, therefore restrict B quality level was assumed.

Results of experimental trial joint are similar to numerical simulations data. Some differences in fusion zone geometry can be shown, therefore are converged with simulation analysis. Wider fusion zone of stainless steel are related to lowest thermal conductivity and heat capacity of material [27]. Differences are greater than in simulation, however surface tension and shielding gas convection effect in simulation algorithms was omitted. Therefore obtained fusion zone geometry are not uniform (Figure 7).

Figure 7: Trial laser welded butt joint in cross section

Structure of base material for 316L was austenitic and for S235JR was ferritic-pearlitic. Microstructure of obtained weld was assumed as a dendritic and are related to crystallization direction. Heat affected zone shown differences in structure over base materials. In austenitic steel grain refining (Figure 8) and in low carbon steel grain growth (Figure 9) was observed [28].

Figure 8: Structure of weld and HAZ of 316L steel

Structure of obtained weld is uniform, no differences in grain size and dendrite growth direction was observed. HAZ size for both material are slightly different, in low carbon steel grain gradually growth, in austenitic steel refining of grain are more abruptly, chemical compounds in stainless steel increase hardenability and have great affect on welded material crystallographic structure. Chemical composition of obtained weld, especially equivalent of chromium, nickel and molybdenum affect on joint properties [29]. In order to define butt weld joint strength characteristic destructive tests need to be performed.

Figure 9: Structure of HAZ and weld of S235JR steel

4 Properties of obtained trial joint

Melting and solidification process changes the crystallographic structure affecting on strength characteristics. Due to welding of dissimilar joint important is that obtained weld and HAZ of both welded materials have similar properties. Due to investigate quality of obtained joint micro hardness testing in cross-section was carried out, without additional post weld heat treatment. Hardness test was carried out according to PN-EN ISO 6507-1 using Innovatest Nexus 4303 machine. Figure 10 shown distribution of test points, Figure 11 shown results of hardness.

Figure 10: Point distribution of measured hardness test in laser welded dissimilar joint

Value of obtained hardness in fusion zone exceed 420HV10, and are considerably great, small increase of hardness in HAZ (188 to 219HV10) towards BM. However high value of weld hardness (419 to 429HV10) proves of material hardening. Mixture of low carbon and stain-

Figure 11: Hardness value in measured test points

less steels chemical elements affect on increase equivalent value of carbon and hardenability elements such as chromium in fusion zone. Therefore high temperature gradient affect on solidification and crystallization process. During mixing of molten materials, chemical composition of fusion zone change and hardening process occur.

5 Chemical composition of obtained dissimilar joint

Hardening in weld are effect of crystallographic change in fusion zone. Mixing of chemical compounds during melting and solidification process affect on weld properties. Properties of weld can be assume as uniform when high mixing factor can be obtained, therefore in order to define uniform weld structure, quality and quantity

Figure 12: Measure line of HAZ and weld of S235JR steel for chemical analyze

Figure 13: Ferrite amount alongside measurement line

Figure 14: Chromium amount alongside measurement line

Figure 15: Measure line of HAZ and weld of 316L steel for chemical analyze

Figure 16: Ferrite amount alongside measurement line

Figure 17: Chromium amount alongside measurement line

energy-dispersive X-ray spectroscopy analysis (EDS) using scanning electron microscope was performed (Figure 12-17). Chemical composition of obtained dissimilar but joint shown uniform mixture of fusion zone, and negligible diffusion in edgewise of weld.

Results of energy-dispersive X-ray spectroscopy analysis shown uniform mixture of fusion zone, and differences between base materials and weld. Chemical composition of obtained weld affect on mechanical properties of joint. Diffusion of chromium and nickel from 316L to weld improve hardenability. Obtained weld structure of dissimilar joint was assume as a dendritic. Moreover some diffusion in overhear zone can be observed. Greater differences alongside fusion line in low carbon steel of ferrite and chromium distribution can be observed.

6 Discussion

The paper presents possibility of using numerical simulation for estimating welding parameters of the dissimilar low carbon S235JR and stainless 316L steels joint. According to established boundary conditions with HS geometry and parameters, parameters for full welding penetrations was obtained. Therefore based on estimated parameters with trial joint using CO₂ laser with speed rate of 1m/min and output power equal to 6kW was carried out. Obtained weld is similar to simulation results, both in simulation and experiment weld width are greater over stainless steel side, however bigger differences are shown in trial joint. This results can be related to phenomena override in numerical simulation like surface tension and shielding gas flow creating forced convection effect results in greater heat removal. Properties of dissimilar but joint based on stress-strain analysis and hardness test was investigated. Therefore maximum effective stress equal to 562MPa occur in stainless steel, however in low carbon steel not exceed 340MPa. Moreover yield stress analysis shown maximum value equal to 557MPa in stainless steel, with 270MPa in low carbon steel. Stress concentration is not uniform, and occur across fusion line in overheat zone. Properties of joint are related to chemical composition of welded materials and process parameters, therefore hardness test using Vickers method with load force equal to 10kgF was performed. Hardness distribution is relative uniform, slightly hardening in S235JR steel HAZ (not exceed 200HV10 with 138HV10 of BM), and uniform value of BM and HAZ in 316L steel (202 to 228HV10). However in fusion zone occur typical hardening effect, where maximum hardness number are 429HV10. Measured value exceed maximum allowable value (350HV10), therefore for industrial application additional post weld heat treatment is required.

Microstructure of obtained weld is with dendritic with dendrites growth related to crystallization direction. Structure of HAZ are characteristic for welded material, and in austenitic steel grain refining is observed, nevertheless in low carbon steel occur grain growth phenomena. In S235JR steel typical overheated, normalization and partial recrystallization zone can be observed. Weld mixture factor was studied using EDS quantity method, where ferrite and chromium distribution in cross section of weld was tested. Distribution of chromium and ferrite have characteristic similar to linear, therefore decrease of chromium and increasing of ferrite in weld comparing to BM of 316L steel, and opposite situation for BM of S235JR can be observed. Nevertheless uniform ferrite and chromium distri-

bution in fusion zone prove high mixing factor of obtained joint.

7 Conclusion

Based on the obtained results, it can be stated that:

- establishing accurate boundary conditions and HS properties laser welding parameters for dissimilar joint can be estimated.
- laser welding technology without additional material can be used for carried out joining of low carbon with stainless steel
- based on thermo-mechanical analysis stress-strain study of joint properties can be performed
- obtained hardness exceed 350HV10, and for industrial applications additional heat treatment are required
- obtained weld have uniform chemical composition with high welded materials mixture factor
- developed laser welding technology can be used for welding of low carbon and stainless steel in industrial applications, however obtained joint require additional post weld heat treatment
- further analysis of mechanical properties such as tensile strength test and corrosion test are planned in future in order to obtained complete weld characteristics [30].

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References

- [1] Iordachescu D, Scutelnicu E, Iordachescu M, Valiente A, Ruiz-Hervias J, Ocaña JL. Specific properties of ferritic/austenitic Dissimilar Metals Welded Joints. *Weld World*. 2011, 55, 2–11, DOI: 10.1007/BF03321280
- [2] Pouranavari M, Marashi SPH. Similar and dissimilar RSW of low carbon and austenitic stainless steels: effect of weld microstructure and hardness profile on failure mode. *Mater Sci Tech-lond*. 2009, 25, 1411-1416, DOI: <https://doi.org/10.1179/026708309X12459430509292>
- [3] Steen WM, Mazumder J. *Laser Material Processing*. Springer. 2010, DOI: 10.1007/978-1-84996-062-5
- [4] Khan MMA, Romoli L, Fiaschi M, Dini G, Sarri F. Laser beam welding of dissimilar stainless steels in a fillet joint configuration. *J Mater Res Technol*. 2012, 212, 856-867, DOI:

- 10.1016/j.jmatprotec.2011.11.011
- [5] Weglowski M, Błacha S, Phillips A. Electron beam welding – Techniques and trends – Review. *Vacuum*. 2016, 130, 72-92, DOI: 10.1016/j.vacuum.2016.05.004
 - [6] Danielewski H, Skrzypczyk A. Properties and Microstructure of Laser Welded VM12-SHC Steel Pipes Joints. *Arch Metall Mater*. 2016, 61, 1143-1149, DOI: 10.1515/amm-2016-0191
 - [7] Elaragi GA. Design and Operation of First Egyptian IEC Fusion Plasma Device. *Emerg Sci J*. 2019, 3, 241-248, DOI: 10.28991/esj-2019-01186
 - [8] Sun Z, Ion JC. Laser welding of dissimilar metal combinations. *J Mater Sci*. 1995, 30, 4205–4214, DOI: <https://doi.org/10.1007/BF00361499>
 - [9] Behúlová M, Babalová E, Sahul M. Design of Laser Welding Parameters for Joining Ti Grade 2 and AW 5754 Aluminium Alloys Using Numerical Simulation. *Adv Mater Sci Eng*. 2017, 1-15, DOI: <https://doi.org/10.1155/2017/3451289>
 - [10] Kuryntsev SV, Morushkin AE, Gilmudinov AKh. Fiber laser welding of austenitic steel and commercially pure copper butt joint. *Opt Lasers Eng*. 2017, 90, 101-109, DOI: 10.1016/j.optlaseng.2016.10.008
 - [11] Kumar KS. Numerical Modeling and Simulation of a Butt Joint Welding Of AISI 316L Stainless Steels Using a Pulsed Laser Beam. *Mater Today Proc*. 2015, 2, 2256-2266, DOI: <https://doi.org/10.1016/j.matpr.2015.07.246>
 - [12] Turňa M, Taraba B, Ambrož P, Sahul M. Contribution to Numerical Simulation of Laser Welding. *Phys Procedia*. 2011, 12, 638–645, DOI: 10.1016/j.phpro.2011.03.080
 - [13] Esfahani R, Coupland J, Marimuthu S. Numerical simulation and experimental investigation of laser dissimilar welding of carbon steel and austenitic stainless steel. *Proc SPIE*. 2015, 9567, DOI: 10.1117/12.2176026
 - [14] Laftah A, Mohammed AH, Abdul-Razzaq KS. Finite Element Analysis and Optimization of Steel Girders with External Prestressing. *Civil Eng J*. 2018, 4, 1490-1450, DOI: 10.28991/cej-0309189
 - [15] Koňár R, Mičian M, Zrak A. Lap weld joint modelling and simulation of welding in programme SYSWELD. *MATEC Web Conf*. 2018, 157, DOI: 10.1051/mateconf/201815702018
 - [16] Deng D, Murakawa H. Numerical simulation of temperature field and residual stress in multi-pass welds in stainless steel pipe and comparison with experimental measurements. *Comput Mater Sci*. 2006, 37, 269-277, DOI: 10.1016/j.commatsci.2005.07.007
 - [17] Zhang GD, Zhou CY. Numerical Simulation of Welding Residual Stress and Post-Weld Heat Treatment for Dissimilar Steel Welded Joint. *Mater Sci Forum*. 2008, 575–578, 747–752, DOI: <https://doi.org/10.4028/www.scientific.net/msf.575-578.747>
 - [18] Danielewski H. Laser welding of pipe stubs made from super 304 steel. Numerical simulation and weld properties. *Techn Trans*. 2019, 1, 167–176, DOI: 10.4467/2353737XCT.19.011.10051
 - [19] Kumar P, Sinha AN. Studies of temperature distribution for laser welding of dissimilar thin sheets through finite element method. *J Braz Soc Mech Sci*. 2018, 40, 455, DOI: <https://doi.org/10.1007/s40430-018-1380-5>
 - [20] Koo BS, Thasanaraphan P, Nied HF. Numerical simulation of the formation of hourglass welds during laser welding. *J Mater Process Tech*. 2019, 263, 176-185, DOI: 10.1016/j.jmatprotec.2017.12.015
 - [21] D'Ostuni S, Leo P, Casalino G. FEM Simulation of Dissimilar Aluminum Titanium Fiber Laser Welding Using 2D and 3D Gaussian Heat Sources. *Metals-Basel*. 2017, 7, 1-15, DOI: <https://doi.org/10.3390/met7080307>
 - [22] Esfahani R, Coupland J, Marimuthu S. Numerical simulation of alloy composition in dissimilar laser welding. *J Mater Process Tech*. 2015, 224, 135-142, DOI: <https://doi.org/10.1016/j.jmatprotec.2015.05.005>
 - [23] Sundqvist J, Kim KH, Bang H-Se, Bang H-Su, Kaplan AFH. Numerical simulation of laser preheating of friction stir welding of dissimilar metals. *Sci Technol Weld Joi*. 2018, 23, 351-356, DOI: 10.1080/13621718.2017.1391936
 - [24] Prabakarana MP, Kannan GR. Optimization of laser welding process parameters in dissimilar joint of stainless steel AISI316/AISI1018 low carbon steel to attain the maximum level of mechanical properties through PWHT. *Opt Laser Technol*. 2019, 112, 314-322, DOI: 10.1016/j.optlastec.2018.11.035
 - [25] Radek N, Pietraszek J, Goroshko A. The Impact of Laser Welding Parameters on the Mechanical Properties of the Weld. *AIP Conf Proc* 2017. 2018, 1, 020025, DOI: <https://doi.org/10.1063/1.5056288>
 - [26] Hamdan AI. Stress Concentration Factors (SCFs) in Circular Hollow Section CHS-to-H-shaped Section Welded T-Joints under Axial Compression. *Civil Eng J*. 2019, 5, 33-47, DOI: 10.28991/cej-2019-03091223
 - [27] Pankaj P, Tiwari A, Bhadra R, Biswas P. Experimental investigation on CO2 laser butt welding of AISI 304 stainless steel and mild steel thin sheets. *Opt Laser Technol*. 2019, 119, 105633, DOI: <https://doi.org/10.1016/j.optlastec.2019.105633>
 - [28] Ramkumar DK, Dev S, Prabhakar KVP, Rajendran R, Mugundan KG, Narayanan S. Microstructure and properties of Inconel 718 and AISI 416 laser welded joints. *J Mater Process Tech*. 2019, 266, 52-62, DOI: <https://doi.org/10.1016/j.jmatprotec.2018.10.039>
 - [29] Yao Ch, Xu B, Zhang X, Huang J, Fu J, Wu Y. Interface microstructure and mechanical properties of laser welding copper–steel dissimilar joint. *Opt Laser Eng*. 2009, 47, 807-814, DOI: <https://doi.org/10.1016/j.optlaseng.2009.02.004>
 - [30] Scendo M, Trela J, Radek N. Influence of laser power on the corrosive resistance of WC-Cu coating. *Surf Coat Tech*. 2014, 259, 401-407, DOI: <https://doi.org/10.1016/j.surfcoat.2014.10.062>