INVESTIGATION OF PROPERTIES OF WAAM PRODUCED DUPLEX STAINLESS STEEL PART

Angela Topić[1], **Ivica Garašić**[2], **Ivan Jurić**[2], **Nikola Knezović**[1]

[1] Fakultet strojarstva, računarstva i elektrotehnike, Sveučilište u Mostaru, Matice hrvatske bb, 88000, Mostar, Bosna i Hercegovina
[2] Fakultet strojarstva i brodogradnje, Sveučilište u Zagrebu, Ivana Lučića 5, 10000, Zagreb, Hrvatska

Abstract

Additive Manufacturing (AM) is a technique whereby freeform structures are produced by building up material in a layer-by-layer fashion. Most of AM technologies use powder material as feedstock and different heat sources, so different kind of problems can occur. WAAM (Wire and Arc Additive Manufacturing) is a technology which has been investigated in the last 30 years, although the first patent was introduced almost 100 years ago. It became popular and interesting to investigate due to its ability to produce fully dense metal parts and large near-net-shape product. One of the potential future WAAM applications could be producing duplex stainless steels. Their excellent corrosion resistance and high mechanical strength make them a favorable choice for oil and gas industrial sectors or off-shore applications. Since they are more difficult to machine than other stainless steels due to their high strength and high work hardening rate, WAAM could overcome some problems which occur in their production. In this paper, chemical composition, hardness and microstructure of duplex stainless steel parts produced using WAAM, are investigated. Different sets of parameters were tested until the most optimal one was chosen, and WAAM product (wall) was made with MIG welding method, using the robotic station.

Keywords: *welding wire, electric arc, duplex stainless steel, hardness, microstructure*

Corresponding author: Nikola Knezović, nikola.knezovic@fsre.sum.ba

1. INTRODUCTION

1.1. WAAM (Wire and Arc Additive Manufacturing)

Thanks to the development of modern industries, there is always a continuous need for investigating and developing new technologies. One of the examples is the aerospace industry, which will need about 20 million tons of billet material in next 20 years [1]. Considering the fact it uses materials like titanium, which is expensive to produce and not so suitable for machining, it is understandably why it was needed to find a better solution. Additive manufacturing (AM) technologies are one of the solutions. Basic AM system consists of a combination of a motion system, heat source and feedstock. Unfortunately, most conventional AM technologies use polymer materials or powdered metal, which is not enough to make a fully functional product often.

Development of WAAM (Wire and Arc Additive Manufacturing) offers the solution for solving issues related to most other AM technologies. WAAM has been investigated since the 1990s, although the first patent dates from 1925 [2]. WAAM uses electric arc as the heat source and metal wire as feedstock, which makes it a combination of welding and AM technology. Also, WAAM uses ordinary welding equipment (power source, torch and wire feeding systems), but combines it with robotic systems or CNC machines which move the torch and wire feeder.

It is considered to be a promising technology for producing fully functional metal products (especially aerospace components), which are almost unlimited by size. High deposition rate, low cost and safer operation makes it desirable [3]. However, there are still challenges to be resolved, like the residual stresses and distortion due to excessive heat input, anisotropic mechanical properties, relatively poor part accuracy and surface finish (post-processing is needed) [4,5]. Some of these problems are already reduced, but there are still problems for researches in the future.

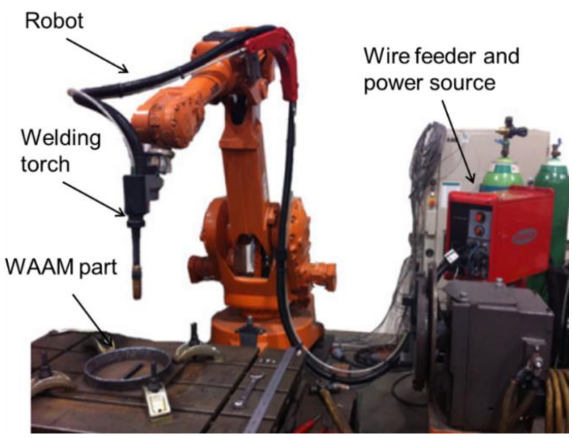

Fig. 1: Example of WAAM system (right) [6]

Like any other AM technology, WAAM starts with designing a 3D CAD model, using software intended for that, or, in recent years, using reverse engineering processes (like 3D scanning). The designed part is then saved in some standard format (usually .stl), which provides a basis for slicing part into layers. Layer's 2D contour is used for generating the tool path and then it is followed by choosing suitable welding parameters (wire-feed rate, travel speed, etc.) and bead modelling. Using generated tool path and chosen welding parameters, the product is then made in layer-upon-layer fashion (the first layer is deposited on the base plate, torch goes up and deposit the second layer onto it, and the process continues until whole part is made) [7]. Post-process machining path can be generated, or post-processing is done independently. Also, heat treatment can be done after. Example of WAAM system is shown in Fig. 1, with its main features.

MIG is the welding method which is mostly used in WAAM technology. The wire is coaxial with the welding torch, and it results in an easily generated tool path. TIG or plasma arc welding are used for producing titanium parts.

1.2. Duplex stainless steels

Stainless steels (also known as Inox, Edelstahl or Rostfrei steels) are the group of steels which are known mostly for their excellent corrosion resistance. According to their microstructure, they can be martensitic, ferritic, austenitic or duplex (austenitic/ferritic). [8]

Duplex stainless steels are the most interesting for research purposes amongst these, due to their mixed microstructure (about 50 % of austenite and 50 % of ferrite). The combined lattice arrangement gives greater strength and offers excellent resistance against Stress Corrosion Cracking (SCC) [9]. Duplex stainless steels solidify as ferrite which partially transforms to austenite during the temperature fall. [10]

They were produced first in Sweden in 1930. Nowadays, duplex stainless steels are usually divided into five groups, according to their corrosion resistance and chemical composition (their corrosion resistance depends on the alloy content). They are ranging from the lower alloyed lean grades to highly alloyed hyper duplex grades. [11]

Major alloying elements are divided into two groups: ferrite promoting (alphagenous) elements (Cr, Mo, W, Nb, Si, Ti, V) and austenite promoting (gamagenous) elements (Ni, Mn, C, N, Co, Cu). Amongst these elements, the most important are Cr and Ni. [12]

Generally, good properties of duplex stainless steels can be achieved when austenite and ferrite both are ranging from 30 % to 70 %, including welded metal, but usually, it should be managed to obtain roughly equal amounts (slightly more austenite due to better toughness). The cooling rate during welding, the chemical composition of steel and the wire and the shielding gas are the most important factors for obtaining the desired structure. [13]

Since any material's successful application mostly depends on the possibility to fabricate different products easily and with minimum cost, that is a limitation for duplex stainless steels, due to problems and the difficulties during welding and machining. Welding is quite complex because of numerous alloying elements, and slow cooling or more cycles of heating to temperature ranges from 600 °C to 1000 °C may result in the formation of detrimental intermetallic phases, particularly in highly-alloyed grades. These phases: sigma (σ), chi (χ), alpha prime (α') and chromium nitride (Cr_2N) have been reported elsewhere and their harmful effect is well-known [14,15]. Due to ferrite presence, duplex stainless steels should not be used below -40 °C, because they undergo ductile-brittle transition. Higher temperature limit is 300 °C, due to an evolution of intermetallics on higher temperatures. Also, they are typically difficult to machine, because of low sulfur content, high work-hardening rate and high yield strength.

1.3. Justification of an idea

Since WAAM produces near-net-shape products, it could offer a solution as an innovative technology for producing duplex stainless steels. Problems which usually occurs during welding can be solved or at least reduced by choosing an appropriate base and additional materials. WAAM has the advantage of using welding wire solely, so there is no need to look for matching additional material. Different welding parameters could be tested and chosen to manage heat input and cooling rate can also vary. Also, to the authors' best knowledge, only authors in paper [16] were conducting researches similar to this so far, so idea to produce duplex stainless steel parts with WAAM technology is justified.

The objective of this study was to investigate the chemical composition, hardness and microstructural evolution of duplex stainless steel part produced using WAAM technology, to better understand the relationship between welding parameters, microstructure and properties of this material.

2. EXPERIMENTAL PROCEDURE

An experiment was carried out in Welding Laboratory at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. Welding robot station (Daihen Varstroj) was used, with robotic hand OTC Almega AX-V6, (six axes of freedom), MIG welding machine DP - 400 and wire feeder CM – 7401. Additional material was 1,2 mm diameter duplex stainless steel welding wire classified as 1,4462, suitable for welding duplex stainless steel 2205. Shielding gas was Inoxline C2 containing 97,5 % Ar and 2,5 % CO_2. Base material was 1,4301 (AISI 304) stainless steel plate, 320x150x8 mm.

After some try-outs with different sets of parameters, four sets were chosen as appropriate, which is shown in Fig. 2.

Fig. 2: Different sets of parameters for the first layer

These four sets fulfilled minimum requirements for arc energy for this duplex grade (0,4 kJ/mm), which is calculated using equation (1):

$$AE\ [kJ/mm] = \frac{I \cdot V \cdot 60}{1000 \cdot v} \qquad (1)$$

where I is current used, V is voltage used, and v is welding speed.

Four sets with their parameters are shown in Tab. 1. Set B gave the widest bead, but the arc was somewhat unstable and some humps can be clearly seen. Similar situation was with set A. Sets C and D still fulfilled minimum requirements for arc energy, but set C have shown similar problems as A and C. On the other side, set D provided stable arc and smooth weld, without any problems during first layer deposition and it was chosen as an appropriate to work with.

Tab. 1: Different sets of welding parameters

Label	Welding current (A)	Voltage (V)	Welding speed (cm/min)	Bead width (mm)
A	140	17	25	7,5
B	125	17	22	8
C	125	17	25	7
D	130	17	25	7

Initial five test layers were deposited with the chosen set of parameters and problems with arc stability occurred immediately during the start of second layer deposition. Numerous humps appeared, probably due to the fact that heat loss is slower during the second layer deposition than at the first one (where base plate is taking away a significant amount of heat). As the layers go up, heat loss is even slower and the problem with humping is getting more significant. The solution was to increase welding speed to 26 cm/min for the second layer, and to 27 cm/min for third and every other layer until the last one. Greater welding speed would compromise arc energy requirements, and 27 cm/min have shown satisfying results, so it was chosen as upper limiting value.

After this correction, final parameters have been inserted into the robot welding program. The plate was cleaned and degreased using 96 % ethanol solution, and the wire was deposited layer by layer onto the substrate with a single bead without weaving. For each successive layer, the deposition direction was reversed and the torch was moved up for 2,5 mm (average layers height measured during the experiments). Delay between deposition for two layers was one minute, just how much is necessary to clean the last deposited layer before the next one is deposited. The interpass temperature was measured after every five passes, but intentionally it was not controlled because it would compromise process speed. Interpass temperatures are shown in Tab. 2. The interpass temperature was measured using the infrared thermometer Fluke 566/568.

Tab. 2: Interpass temperature

Layer	1st	6th	11th	16th	21st	26th	30th
Temperature (°C)	120	150	180	215	250	290	330

Totally, 30 layers were deposited in one hour and 15 minutes. The produced wall was 300 cm long and 66 cm high and it is shown in Fig. 3.

Fig. 3: Deposited WAAM wall

After the deposition, 40 mm from both sides were removed as unusable, and the wall was cut to two identical parts, 110 mm long. One of those parts was used for examinations and testings which are described in this paper. Specimens for micro- and macro-structure observations and hardness testing were ground after cutting with SiC paper (granulations P120, P320, P500, P1000, P2000, P4000, respectively) and etched in 10% oxalic acid for three minutes.

Microstructure and macrostructure were examined using light microscope Olympus GX 51. Hardness was measured using Reicherter Brivisor KL2 hardness tester, according to ISO 6507-1:2005. Chemical composition was determined using X-Ray fluorescence spectroscopy method, with DELTA Alloys and Metals Handheld XRF Analyzer.

3. RESULTS AND DISCUSSION

3.1. General observations

Deposited wall showed good geometric characteristics – there was no distortion and it stayed perpendicular to the base plate. Problems with distortion occurred along the vertical axis at both ends, where layers pulled the base plate up more than it was expected. More rigid clamping or thicker base plate is necessary to avoid this problem in the future. Aesthetically, the wall also looked good, there were no significant height deviations across the whole length (except the ends). However, reversing the deposition direction after every pass reduced accumulation of more significant defects on the wall ends. It is important to mention the total height, which was cca. 60 mm after 30 layers. According to the first experiments, the average layer height was 2,5 mm, so that was the input value for the robot (to raise the torch along the vertical axis after every layer). Obviously, the average layer height is getting lower after certain passes, probably due to the fact that more wire is melted on the wall sides at the latter passes. However, it did not affect wall width significantly. Further experiments should include measuring every layer height to get better and more precise results. The main problem that can be seen on first sight is pores, occurring on both lateral sides of the wall, especially after the first five or six layers (Fig. 4, a). The reason for this could be a fact that shielding gas can not provide enough protection after a certain number of passes, due to its loss in the surrounding air. While the torch is still low, base plate deflects some part of shielding gas, creating some kind of pool which protects first few passes, but when the torch is higher, protection becomes weaker. However, these pores are shallow and only affects the surface. Considering a fact that only 1 mm of deposited layers were milled from both of the lateral sides, and pores have not affected material at the inside (Fig. 4, b), they should not be a problem when making thinner structures. When it comes to structures with a thicker wall, where bead overlapping is inevitable, these pores could be a significant problem. The inclusion of additional gas nozzles from the lateral sides or even plates that would help create and maintain shielding gas pool could be a good solution.

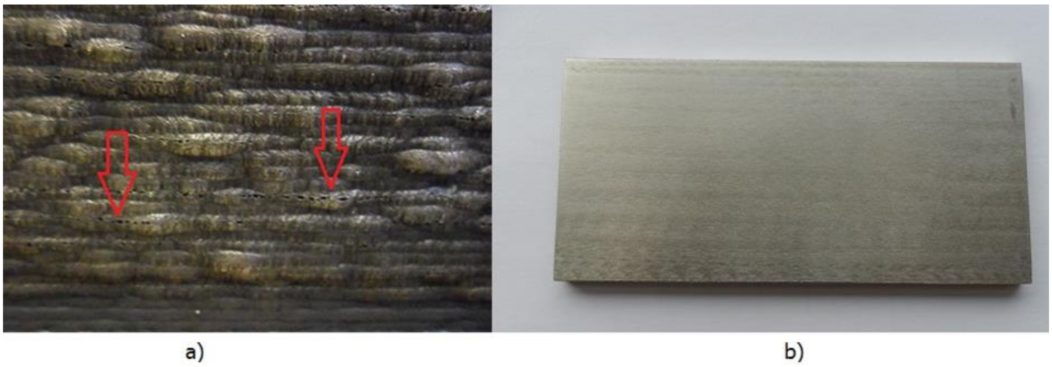

Fig. 4: Pores on lateral sides (a); deposited wall after milling (b)

3.2. Chemical composition

The chemical composition of the deposited wall was measured at three different points. The values were averaged then and they are shown in Tab. 3.

Tab. 3: Chemical composition of the deposited wall

Element	Deposited wall (%)	Wire (%)
Si	0,46	0,37
P	0,01	0,013
Cr	22,78	22,8
Mn	1,54	1,63
Ni	8,83	8,76
Cu	0,16	0,05
Mo	3,15	3,15

All main alloying elements (Cr, Ni, Mn and Mo) did not suffer any significant changes. That was expected, due to the fact that there was no mixing between the base and additional material like it happens in welding. Only Cu and Si amounts have been changed – both of them increasing in the deposited wall. Cu is a gamagenous element, while Si is an alphageonus element, and their amounts are low, so phases should stay in balance and these changes should not be significant, but detailed microstructure characterization is necessary to prove that. Fig. 5 shows a comparison of chemical composition between the deposited wall and the wire.

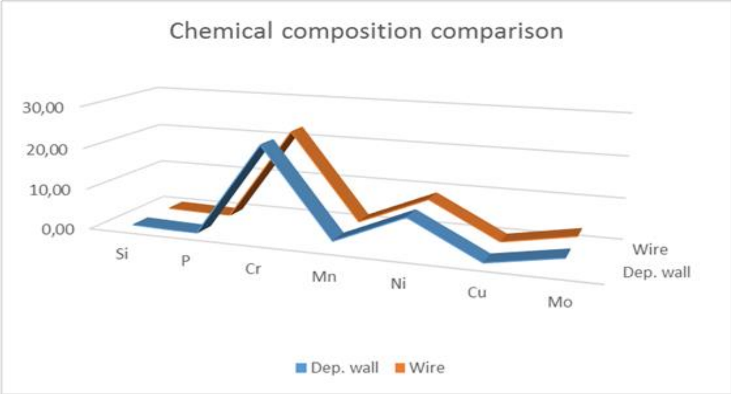

Fig. 5: Chemical composition comparison between the deposited wall and the wire

3.3. Macrostructure and microstructure observations

The macrostructure of the deposited material is shown in Fig. 6. Specimens were extracted from the one end of the wall (Fig. 6., a) and from the middle of the wall (Fig. 6., b), parallel to the vertical axis (building direction). There is no any significant differences between these two parts, which suggests the deposited material is quite homogenous across its cross-section along a y-z plane (from the one end of the wall to another). It means it is enough to provide specimen anywhere from the wall for further experiments to obtain satisfying results. Macroscopic banding, corresponding to each layer height, is not easily visible, unlike some other materials like titanium [17].

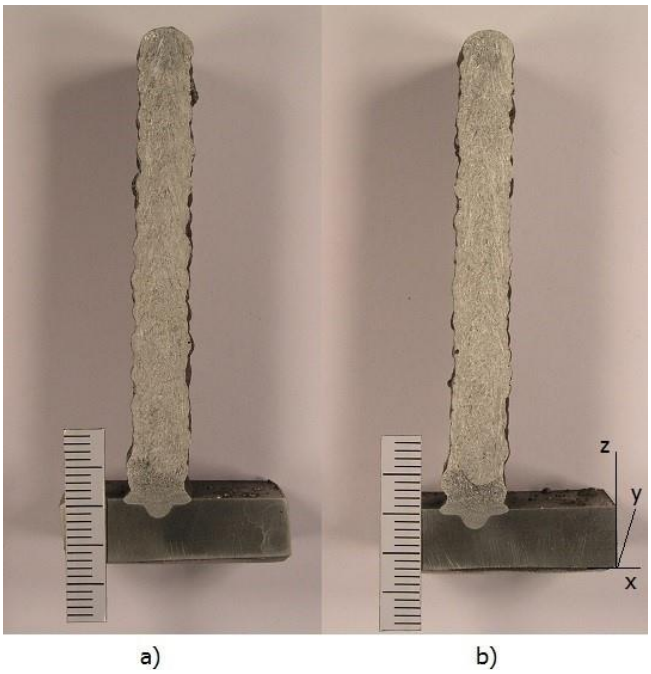

Fig. 6: Macrostructures of the end (a) and the middle of the wall (b)

The microstructure is shown in Fig. 7. Austenite is a brighter phase and ferrite is a darker phase. Obviously, there is more austenite, but further and more detailed testing is necessary to confirm that. Dendritic structure with longer grains growing in the vertical direction can be clearly seen. Smaller grains segregated and grew at the sides of longer ones. Black dots are probably carbides which occur because of poor shielding gas protection at higher layers or defects made during cleaning and preparing for the examination. Longer grains in building direction are probably created by merging more grains from different layers (during deposition of a particular layer, heat could melt previous layer and grains could merge).

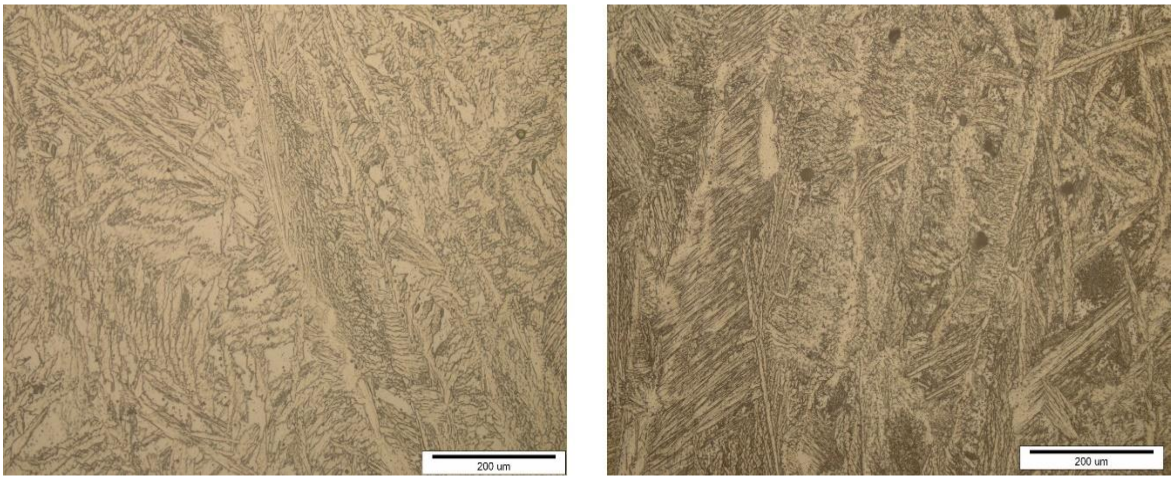

Fig. 7: Microstructure of the deposited wall

3.4. Hardness testing

Fig. 8 shows the arrangement of measuring points for hardness. Point 1 is an area of last two deposited layers, points 2 and 3 are middle layers band, point 4 is an area of first two deposited layers, point 5 is fusion line and HAZ (heat affected zone), while the point 6 is base material. Three different measures were executed at each point and then the values were averaged and recorded. Force of 98,04 N (10 kp) was used.

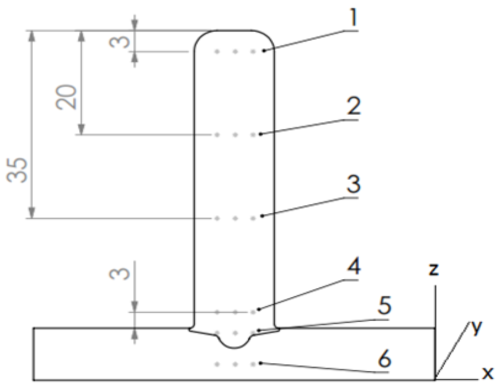

Fig. 8: Points for microhardness measuring

It can be seen in Tab. 4 and Fig. 9 that both specimens have similar hardness, with no significant differences, except on the top band (point 1). Specimen 1 was cut from the end of the wall and it shows higher hardness than specimen 2 (cut from the middle of the wall) at the same place (11,5 % higher). The reason for this could be the fact that end of the wall had higher cooling rate and was more prone to oxidation because arc was stopped after depositing final layer and shielding gas did not provide enough protection, while the middle part of the same layer experienced slower cooling and better gas protection. Point 5 has lower hardness, probably because some part of the wire melted and mixed with the base austenitic plate. The most important information is that the middle band (points 2, 3 and 4) have almost the same hardness values, which means properties are homogenous in the largest part of the wall.

Tab. 4: HV10 hardness for both specimens

Point	Specimen 1 (HV10)	Specimen 2 (HV10)
1	308,3	276
2	250,7	260,2
3	255,7	257
4	250,3	247,3
5	224,3	233,7
6	199,2	198,7

Compared to the mechanical properties of the wire used, hardness increased only for cca. 4 %, which should not affect other properties significantly. Also, standards EN 10088-3:2014 and EN 10088-5:2009, which define technical delivery conditions for different types of duplex stainless steel products, require a maximum of 270 HB for products thinner than 160 mm. It is roughly equal to 277 HV, which means only last few passes do not fulfil that requirement. However, since the first few and last few layers are planned to be cut during machining (prior to the application of the part), it is important to know that main part of the wall have satisfying and homogenous properties.

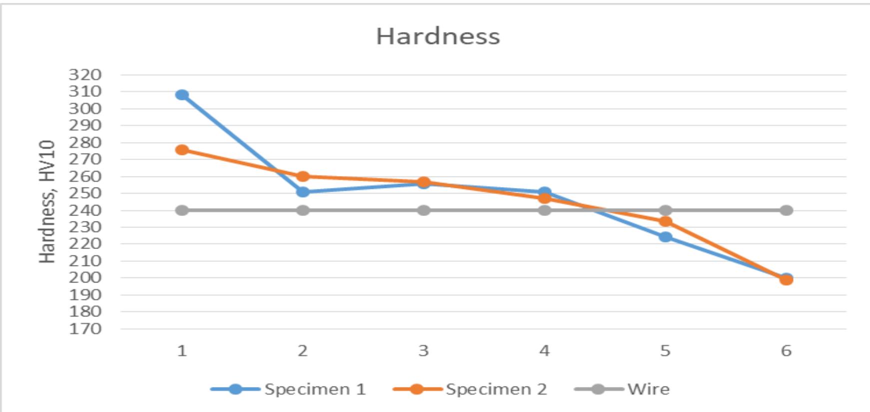

Fig. 8: Hardness profiles for both specimens compared

4. CONCLUSIONS

The potential for fabricating near-net-shape duplex stainless steel components with WAAM technology has been demonstrated in this article. The chemical composition, hardness and microstructure of as-deposited part have been investigated and it has been shown it is possible to achieve acceptable mechanical properties.

a) Generally, the deposited wall showed good quality. Some pores occurring on the lateral wall sides have been reported. Though they are shallow and do not affect material (except the part which is machined anyway), problems with producing parts with thicker walls could occur. Further investigations should include ideas for solving this issue (additional shielding gas nozzles from both sides of the wall or plates that would create and maintain shielding gas pool). Average layer height is obviously lower than assumed 2,5 mm, so further experiments and researches should include measuring every layer's height before depositing next one. The interpass temperature has only been measured in this experiment, and controlling it in further experiments could be a valuable addition to researches in this topic. More rigid clamping or some other strategy should also be considered for solving distortions issues.

b) The chemical composition of the as-deposited wall is almost the same as the wire chemical composition, which was expected because there was no mixing between materials, except the first layer that was melted and mixed with the base plate.

c) Homogenous macrostructure has been observed from one end of the wall to the another. Microstructure showed some anisotropy (longer grains in building direction), but testing of more mechanical properties have to be done to see if there is any influence.

d) Hardness was lower near the bottom and higher at the top, but the majority of the part has a hardness similar to designated wire hardness (cca. 4 % higher) and in the acceptable range of appropriate standards (comparable to parts produced with conventional technologies).

REFERENCES

1. Mehnen J., Ding J., Lockett H., Kazanas P., Design study for wire and arc additive manufacture, International Journal of Product Development, 19(1/2/3), pp. 2–20, (2014).
2. Williams S.W., Martina F., Addison A.C., Ding J., Pardal G., Colegrove P., Wire + Arc Additive Manufacturing, Materials Science and Technology, 32(7), pp. 641-647, (2016).
3. Ding J., Martina F., Williams S., Production of large metallic components by additive manufacture – issues and achievements, Proceedings 1st "Metallic Materials and processes: industrial challenges", Deauville, France, (2015).
4. Ding D., Pan Z., Cuiuri D., Li H., Wire-feed additive manufacturing of metal components: technologies, developments and future interests, The International Journal of Advanced Manufacturing Technology 81(1–4), pp. 465–481, (2015).
5. Martina F., Colegrove P.A., Williams S.W., Meyer J., Microstructure of Interpass Rolled Wire + Arc Additive Manufacturing Ti-6Al-4V Components, Metallurgical and Materials Transactions A, 46(12), pp. 6103–18, (2015).
6. Ding J., Colegrove P., Martina F., Williams S., Wiktorowicz R., Palt M.R., Development of a laminar flow local shielding device for wire+arc additive manufacture, Journal of Materials Processing Technology, 226, pp. 99–105, (2015).
7. Ding D., Shen C., Pan Z., Cuiuri D., Li H., Larkin N., et al., Towards an automated robotic arc-welding-based additive manufacturing system from CAD to finished part, Computer-Aided Design, 73, pp. 66–75, (2016).
8. Karlsson L., Stainless Steels: Past, Present and Future, Svetsaren, 1, pp. 1–6, (2004).
9. Olsson J., Snis M., Duplex - A new generation of stainless steels for desalination plants, Desalination, 205(1–3), pp. 104–13, (2007).

10. IMOA, "Practical Guidelines for the Fabrication of Duplex Stainless Steels", 3rd Edition, 2014, IMOA

11. Karlsson L., Welding Duplex Stainless Steels – a Review of Current Recommendations, Welding in the World, 56(05/06), pp. 65–76, (2012).

12. Vinoth J.A., Ajaykumar L., Deepak C.R., Aditya K.V.V., Weldability, machinability and surfacing of commercial duplex stainless steel AISI2205 for marine applications – A recent review, Journal of Advanced Research, 8(3), pp. 183–99, (2017).

13. Outokumpu, Analytical Chemistry, 39(4), pp. 110, (1967).

14. Kang D.H., Lee H.W., Effect of Different Chromium Additions on the Microstructure and Mechanical Properties of Multipass Weld Joint of Duplex Stainless Steel, Metallurgical and Materials Transactions A, 43(12), pp. 4678–4687, (2012).

15. Rede V., Žmak I., Analiza osnovne mikrostrukture i mikrostrukturnih promjena u dupleks-čeliku, Proceedings, Sustainable Development in Foundry Materials and Technologies, Sisak University of Zagreb, Faculty of Metallurgy, pp. 386–393 (2012).

16. Posch G., Chladil K., Chladil H., Material properties of CMT—metal additive manufactured duplex stainless steel blade-like geometries, Welding in the World, 61(5) pp. 873–882, (2017).

17. Wang F., Williams S., Colegrove P., Antonysamy A.A., Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V, Metallurgical and Materials Transactions A, 44(2), pp. 968–977, (2013).