Microstructure and Mechanical Properties of the Wire Arc Additively Manufactured Sv-08G2S Steel

A A Kulikov, A E Balanovskiy and M V Grechneva
Irkutsk National Research Technical University, 83, Lermontov street, 664074, Irkutsk, Russian Federation

Email: the.tosha2013@gmail.com

Abstract. Wire arc additive manufacturing enables using almost any grade of metal for the additive production of parts with complex shapes and large sizes. As an increasingly growing number of materials are being used for WAAM, it is necessary to conduct systematic research on the properties of various metals and alloys. This article presents a study of the microstructure and mechanical properties of the wire arc additively manufactured Sv-08G2S steel. Once the wall-shaped sample was deposited, it was cooled in the air at room temperature. The sample for microstructure studies was cut across the central line of the deposited layers. In the sample, three sectors were conditionally distinguished: the lower sector, deposited on a cold substrate, has a ferrite structure with inclusions of lamellar perlite; the middle sector has a purely ferritic structure; the upper sector has a bainite structure. The microstructure study was followed by hardness measurements performed in all sectors of the sample. The hardness values confirmed the presence of different structures in all sectors, the hardest of which was the upper sector with a bainite structure. The last stage of the study was the tensile testing of the sample performed on a test breaking machine. The obtained values of the ultimate tensile strength and yield strength of additively deposited steel are within the range and even exceed the characteristics of wrought low-carbon steels. Therefore, the conducted research proved that the additive manufacturing of parts made of Sv-08G2S steel enables achieving the necessary quality and provides the mechanical properties required for structural steels.

1. Introduction
The popularity of additive manufacturing (AM) and its rapid development are primarily related to the necessity to develop modern cost-effective manufacturing technologies. AM enables high-performance manufacturing of parts with complex geometric shapes. Another significant advantage of AM is a high material utilization rate. One of the latest technologies for 3D printing of metal products is wire arc additive manufacturing (WAAM). This technology combines industrial robots with off-the-shelf welding equipment. Thanks to the use of welding wires, the WAAM technology has a huge potential for printing almost any metal alloys [1–8]. Compared with the traditional subtractive manufacturing (machining), WAAM has a higher performance (40-60% higher), which helps to reduce the time of the finishing machining by 15-20%, depending on the size of the product [9].

The heat source is an electric arc generated between the substrate and the metal wire [10–13]. Welding wires are used as a feedstock material, which is much cheaper than metal powders used in other additive technologies [14-17]. Along with printing new parts, WAAM can also be used for repair and restoration operations [18].
The production of structurally strong, high-quality, reliable parts requires an understanding of the existing technological processes, underlying physical processes, raw materials, process control methods, and the causes of various defects and ways to eliminate them. In order to produce parts with pre-set properties, it is necessary to understand the principles of the microstructure evolution and mechanical properties of metals during the thermal impact.

As steels are still the most common industrial materials, they are of great interest to the WAAM community. On the one hand, the allotropy of iron-based alloys combined with high-temperature gradients makes it possible to produce products with a unique microstructure. On the other hand, alloys that may have different phase compositions depending on the cooling rate, such as martensite and retained austenite in steels with dispersion hardening will be sensitive to different thermal welding cycles. Therefore, steels are needed to be carefully studied for application in WAAM.

This article presents the following studies of the wire arc additively manufactured Sv-08G2S steel: macrographic and micrographic analysis of the microstructure of steel using a scanning electron microscope, Brinell hardness test, tensile testing of samples to determine the yield strength and ultimate tensile strength.

2. Materials and Methods
A Lorch SpeedPulse S3 mobil welding machine was used for the deposition of the sample. The industrial robot KUKA KR 210 R2700 prime was used as a manipulator of the welding torch. The following modes were used for deposition: welding current 100 A, voltage 26 V, wire feed rate 4.5 m/min, printing speed 3 mm/sec, stickout distance 14 mm. To protect the molten metal from air contaminants a shielding CO2 gas with a flow rate of 10 l/min was used.

The wall was used as a sample (see figure 1) deposited on a Fe37-3FN structural carbon steel plate of 16 mm thickness. The wall has the following dimensions: length 100 mm, height 27 mm, the number of layers 13.

![Figure 1. The deposited wall.](image)

The Sv-08G2S steel welding wire was used as a feedstock material. The chemical composition of this wire is presented in table 1. The sample was cooled in the air at room temperature.

| Table 1. Chemical composition of SV-08G2S wire. |
|------|------|------|------|------|------|------|------|
| C    | Si   | Mn   | Ni   | S    | P    | Cr   | N    |
| 0.06 | 0.8  | 1.9  | 0.2  | 0.02 | 0.02 | 0.1  | 0.01 |

The sample for microstructure studies was cut across the central line of the deposited layers. Optical microscopy of the mechanically polished sample was performed in a cross-section. The sample was etched with Keller's reagent (2 ml HF, 3 ml HCl, and 5 ml HNO3 in 190 ml of water) to reveal the structure of the metal and grains. Electron microscopic studies were carried out on the
basis of the Irkutsk National Research Technical University using a scanning electron microscope JIB-4501 JEOL multi-beam system equipped with an electronic and ion gun JIB-4501, completed with a nitrogen-free system of energy-dispersive microanalysis. The results were analysed using the Channel 5 software package developed by Oxford Instruments. For these purposes, the test sample has additionally passed the electro-polishing stage. The size of the scanning area for a sample was 620 microns. The grain was taken as an area surrounded by large-angle borders, i.e. the value of the limit angle was set to 15°.

The macro- and microanalysis were followed by the Brinell hardness testing along the length of the sample. The measurements present results of evaluating the hardness of sectors of the sample from the first layer to the last. The HBRV – 187.5 hardness testing machine was used for measurements. The sample was used under a load of 7kH for 10 seconds. The HBRV – 187.5 hardness testing machine uses a rotational type of load change mechanism, as well as an optical measurement display system and a measuring microscope mounted on the device body. Polished (Ra < 0.04 microns) balls made of a SHX15 steel with a nominal diameter of 5 mm were used as penetrators. The CDM-20 tensile testing machine was used for tensile testing of the sample.

3. Microstructural analysis

Preparation of the sample (see figure 2) for microstructural analysis includes following stages:

- rough grinding;
- final grinding;
- polishing;
- etching.

Figure 2. Sample for microstructural analysis.

Rough grinding is performed for the leveling of a surface of the sample using an engineer’s file. Then a final grinding follows. Final grinding is performed to minimize surface imperfections using abrasive paper of decreasing grain size. Corundum, carborundum, and other solids are used as abrasives deposited on abrasive papers.

The next stage of preparation is polishing, which is necessary for the final alignment of the surface of the sample. Polishing is carried out using a polishing machine, the working body of which is a rotating disk covered with a fabric.
Etching of the polished sample is performed to reveal a complete picture of the microstructure (grain shape and size, presence of phases, structural components). Before etching, the surface of the sample is degreased with alcohol. The sample is etched with Keller's reagent (2 ml HF, 3 ml HCl, and 5 ml HNO₃ in 190 ml of water) for 10-20 seconds. After etching, the sample is washed with water and dried with filter paper.

The sample for microstructural analysis can be divided into 3 sectors: lower, middle and upper (see figure 3). The lower sector contacts the cold surface of the substrate metal and experiences a certain heat drop. The metal of the middle sector is characterized by a lower temperature difference since the weld beads of this sector are deposited on the preheated metal of the previous beads.

The metal of the upper sector is characterized by a sharper temperature difference since it is in contact with room temperature air. Figure 4 shows the macrostructure of the Sv-08G2S steel in three different sectors.

The macrostructure of the upper sector is significantly different from the macrostructure of the other two sectors. The metal of the lower and middle sectors is characterized by an almost equiaxed structure, while the metal of the upper sector has a lamellar structure. Figure 5 presents the transition zone between the lower and middle sectors. The difference in microstructure and grain size is clearly visible on the transition line.
The microstructure of this transition zone is characterized by a mixture of coarse grains of the lower sector with fine grains of the middle sector. Figure 6 shows the microstructure of the lower sector. Equiaxed grains with inclusions of thin lamellas are observed in this sector [19, 20].

![Figure 6. The microstructure of the lower sector (ferrite+perlite).](image)

Since the metal is deposited on a cold substrate, the first beads experience a significant temperature difference. This contributes to the formation of a microstructure with ferrite grains and inclusions of lamellar perlite. The formation of ferrite with an equiaxed grain shape with inclusions of lamellar perlite is typical for low-carbon steel, which is the welding wire Sv-08G2S.

Figure 7 shows the microstructure of the middle sector. The middle sector is characterized by equiaxed ferrite grains without any inclusions. The microstructure shows that the ferrite of the middle sector has a more coarse-grained structure than in the lower sector. This is due to a higher temperature difference in the lower sector compared with the middle one.

![Figure 7. The microstructure of the middle sector (ferrite).](image)

The metal of the middle sector cools slower than that of the upper sector, so its thermal gradient is lower than that in the lower sector. The metal of the lower sector also cools slower than the metal of the upper sector, which results in the formation of ferrite. The presence of lamellar perlite is explained by a less sharp temperature drop due to the presence of a cold substrate compared with air cooling in the upper sector. Figure 8 shows the microstructure of the upper sector.

![Figure 8. The microstructure of the upper sector (bainite).](image)
As mentioned earlier, it is in this area that a higher temperature drop is observed, so the metal microstructure in this sector is significantly different from others and has a predominantly lamellar structure. In particular, it should be noted that this microstructure is bainite, which is a mixture of ferrite and cementite. Since cooling begins at a temperature about 70 °C above the critical temperature for the steel used, the growth of ferrite particles devoid of carbon occurs. Since the carbon in ferrite is contained in smaller amounts, it passes to the upper sections and the lamellas are filled with carbon.

It is also worth noting that due to the effect of reheating during the deposition of layers, it is possible to achieve the formation of different microstructures along the height of the sample. This enables adjusting the microstructure between ferrite and bainite to obtain the necessary mechanical properties of the product by alternating cooling cycles after the deposition of one or more layers.

4. Hardness testing
Figure 9 shows a diagram with Brinell hardness values. The results obtained show the hardness values in the direction from the lower to the upper sector. The highest values of hardness are observed in the sector with the bainite structure. It is worth noting the almost complete absence of pores, which is a significant advantage in comparison with other additive technologies used for the production of metal products.

The results of hardness measurements confirm the formation of various structures in the sample sectors. Thus, the lower sector, where the structure of ferrite with inclusions of lamellar perlite was formed, has a hardness of 200-220 HB. Higher hardness values of the lower sector compared to the middle sector occur due to inclusions of lamellar perlite.

The middle sector has a purely ferritic structure, which is proved by the lowest hardness values compared with all other sectors. Ferrite is soft and plastic. Ferrite hardness values are in the range of 130-150 HB.

The highest hardness values (260 HB) were found in the upper sector. The bainite structure provides high hardness and strength with high plasticity.

5. Tensile testing
The tensile diagram (see figure 10) shows the dependence of the elongation of the sample on the longitudinal tensile force.

The diagram has four distinctive areas:
OA – proportionality area (0-350 MPa);
AB – elasticity area (350-360 MPa);
BC – yield point area (360-405 MPa);
CD – hardening area (405-577 MPa);
DE – failure area (577-432 MPa).
At the very beginning of the tensile test, the tensile force, and therefore the deformation of the sample, is zero, so the diagram begins at the intersection of the respective axes (point O).

In the OA area, the diagram is drawn as a straight line. This indicates that in this segment of the diagram, the deformations grow in proportion to the increasing load.

Once point A passed, the diagram abruptly changes its direction and in the AB area the line runs almost parallel to the stretching axis for some time, that is, the deformations increase at almost the same load value.

At this point, irreversible changes begin to occur in the metal of the sample. The crystal lattice of the metal is rebuilt. At the same time, the effect of self-strengthening is observed.

After increasing the strength of the sample material, the diagram goes up again (BC area) and at point D the tensile force reaches the maximum value. At this point, a local thinning appears in the working part of the test sample, caused by violations of the material structure (the formation of voids, microcracks, etc.).

Due to thinning, and therefore reducing the cross-sectional area of the sample, the tensile force required to stretch it is reduced, and the curve of the diagram goes down.

The sample breaks at point E which is the thinning zone.

Mechanical properties of the WAAM Sv-08G2S steel and wrought low carbon steels with comparable chemical compositions are shown in table 2.

**Table 2. Mechanical properties of steels.**

| Steel grade | Test temperature, ºC | YS, MPA | UTS, MPa | Elongation, % | Contraction, % |
|-------------|----------------------|---------|----------|--------------|---------------|
| WAAM Sv-08G2S | 20 | 405 | 577 | 31 | 59 |
| 09G2S | 20 | | | | |
| 09G2T | 20 | 265-385 | 430-490 | 17-31 | 56-63 |
| 09G2DT | 20 | | | | |
| 10G2S1 | 20 | 335 | 485 | 35 | 75 |
As can be seen from the table, the mechanical properties of the wire arc additively manufactured Sv-08G2S steel meet properties of conventional wrought low-carbon steels and even exceed them.

6. Conclusion
Based on the results of the study of the macro and microstructure and mechanical properties of the wire arc additively manufactured Sv-08G2S steel, the following conclusions can be drawn:

- The structure of the Sv-08G2S metal can be divided into three sectors depending on the formed microstructure. The lower sector is characterized by a ferritic structure with inclusions of lamellar perlite. The middle sector is characterized by a purely ferritic structure with equiaxed grains. The upper sector is characterized by a lamellar structure of bainite.
- Differences in the microstructure of the sectors are due to various temperature differences and heat input experienced by different deposited beads. In particular, the metal of the upper sector experiences a stronger temperature drop due to the difference in air temperature and the temperature of the lower layers.
- The lower sector is characterized by the presence of smaller particles, so the metal in this sector experiences stronger temperature differences compared to the metal in the middle sector, which is characterized by a larger grain.
- The results of the Brinell hardness study confirm the presence of various microstructures. The hardest was the upper sector, which has a bainite structure.
- The results of tensile testing of samples made of Sv-08G2S steel showed mechanical properties that are comparable and even superior to those of conventional wrought low-carbon steels.
- Thus, this steel can be used for wire arc additive manufacturing of steel parts, since the resulting mechanical properties meet the requirements for structural steels.

Also, based on the results of the research, it is possible to develop a technology to obtain the necessary structure of ferrite/bainite in accordance with the requirements for the manufacturing part. Obtaining the necessary microstructure can be achieved by alternating cooling cycles and deposition cycles.

References
[1] Wu B, Pan Z, Ding D, Cuiuri D 2018 A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. Journal of Manufacturing Processes 35 127–139 DOI: 10.1016/j.jmapro.2018.08.001
[2] Shi X, Ma S, Liu C, Wu Q, Lu J 2017 Selective laser melting-wire arc additive manufacturing hybrid fabrication of Ti-6Al-4V alloy: Microstructure and mechanical properties Materials Science and Engineering: A 684 196–204 Online. Available: https://doi.org/10.1016/j.msea.2016.12.065
[3] Horgar A, Fostervoll H, Nyhus B, Ren X 2018 Additive manufacturing using WAAM with AA5183 wire Journal of Materials Processing Technology 259 68–74 Online. Available: https://doi.org/10.1016/j.jmatprotec.2018.04.014
[4] Zhang C, Li Y, Gao M, Zeng X 2018 Wire arc additive manufacturing of Al-6Mg alloy using variable polarity cold metal transfer arc as power source Materials Science and Engineering: A 711 415–423 Online. Available: https://doi.org/10.1016/j.msea.2017.11.084
[5] Wang J, Pan Z, Yang G, Han J 2019 Location dependence of microstructure, phase transformation temperature and mechanical properties on Ni-rich NiTi alloy fabricated by wire arc additive manufacturing Materials Science and Engineering: A 749 218–222 Online. Available: https://doi.org/10.1016/j.msea.2019.02.029
[6] Ding D, Pan Z, van Duin S, Li H 2016 Fabricating Superior NiAl Bronze Components through Wire Arc Additive Manufacturing Materials 9(8) 652 Online. Available: https://doi.org/10.3390/ma9080652
[7] Wu B, Qiu Z, Pan Z, Carpenter K, Wang T, Ding D 2020 Enhanced interface strength in steel-nickel bimetallic component fabricated using wire arc additive manufacturing with
interweaving deposition strategy *Journal of Materials Science & Technology* **52** 226–234

[8] Ahsan M R U, Tanvir A N M, Bates B, 2020 Heat-treatment effects on a bimetallic additively-manufactured structure (BAMS) of the low-carbon steel and austenitic-stainless steel *Additive Manufacturing* **32** 101036 Online. Available: https://doi.org/10.1016/j.addma.2020.101036

[9] Williams S W, Martina F, Addison A C, Ding J 2016 Wire Arc Additive Manufacturing *Materials Science and Technology* **32**(7) 641–647 DOI: 10.1179/1743284715y.0000000073

[10] Dickens P, Pridham M, Cobb R, Gibson I, Dixon G 1992 Rapid prototyping using 3-D welding (DTIC Document)

[11] Spencer J, Dickens P, Wykes C 1998 Rapid prototyping of metal parts by three-di-dimensional welding *Proc Inst Mech Eng Part B J Eng Manuf* **212** 175–182

[12] Kovacevic R and Beardsley H 1998 Process control of 3D welding as a droplet-based Rapid prototyping technique *Proc. of the SFF Symposium Univ. of Texas at Austin* **57**–64

[13] Dwivedi R and Kovacevic R 2004 Automated torch path planning using polygon subdivision for solid freeform fabrication based on welding *J Manuf Syst* **23** 278–291

[14] Song Y A, Park S, Choi D, Jee H 2005 3D welding and milling: part I—a direct approach for freeform fabrication of metallic prototypes *Int J Mach Tools Manuf* **45** 1057–1062

[15] Song Y A, Park S, Chae S-W 2005 3D welding and milling: part II—optimization of the 3D welding process using an experimental design approach *Int J Mach Tools Manuf* **45** 1063–1069

[16] Zhang Y, Chen Y, Li P, Male A T 2003 Weld deposition-based rapid prototyping: a preliminary study *J Mater Process Technol* **135** 347–357

[17] Zhang Y M, Li P, Chen Y, Male A T 2002 Automated system for welding-based rapid prototyping *Mechatronics* **12** 37–53

[18] Marenych O, Kostryzhev A, Shen C, Pan Z 2019 Precipitation Strengthening in Ni–Cu Alloys Fabricated Using Wire Arc Additive Manufacturing Technology *Metals* **9**(1) 105 DOI: 10.3390/met9010105

[19] Donghong Ding, Zengxi Pan, Dominic Cuiuri, Huijun Li 2015 A multi-bead overlapping model for robotic wire and arc additive manufacturing *Robot Cim-Int Manuf* **31** 101–110

[20] Filippo Montevecchi, Niccolò Grossi, Hisataka Takagi, Antonio Sciappa 2016 Cutting Forces Analysis in Additive Manufactured AISI H13 Alloy *Procedia CIRP* **46** 476–479 Online. Available: http://dx.doi.org/10.1016/j.procir.2016.04.034.

**Acknowledgments**

Anton A. Kulikov prepared the steel sample, conducted the microstructural analysis, mechanical properties testing, and wrote the paper. Maria V. Grechneva contributed to the microstructure and mechanical properties analysis. Andrei E. Balanovskiy carried out the overall project management and participated in the discussion of the results.