Building strategy effect on mechanical properties of high strength low alloy steel in wire + arc additive manufacturing

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Abstract

Wire arc additive manufacturing (WAAM) which is literally based on continuously fed material deposition type of welding processes such as metal inert gas (MIG), tungsten inert gas (TIG) and plasma welding, is a variant of additive manufacturing technologies. WAAM steps forward with its high deposition rate and low equipment cost as compared to the powder feed and laser/electron beam heated processes among various additive manufacturing processes. In this work, sample parts made of low allow high strength steel (ER120SRG) was additively manufactured via WAAM method using robotic cold metal transfer technology (CMT). The process parameters and building strategies were investigated and correlated with the geometrical, metallurgical and mechanical properties on the produced wall geometries. The results obtained from the thin wall sample parts have showed that with increasing heat input, mechanical properties decreases, since higher heat accumulation and lower cooling rate increases the grain size. The tensile tests results have showed that casting steel (G24Mn6+QT2) mechanical properties which requires 500 MPa yield strength can be compared to with as build WAAM process having 640 MPa yield strength. Tensile strength were fulfilled for S690Q and yield strength is very close to the reference value.

1. Introduction

Additive manufacturing (AM) has been defined as a process of joining materials to make objects from 3D model data, usually layer upon layer as opposed to subtractive methodologies [1]. It is a technology that promises to reduce part cost by reducing material wastage and time to market.

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1. Uvod

Aditivna proizvodnja je definisana kao proces spajanja materijala kako bi se napravili objekti na osnovu podataka iz 3D modela, najčešće dodavanjem sloja na sloj, kao suprotnost metodologijama odstranjivanja materijala [1]. U pitanju je tehnologija koja omogućava smanjenje...
Furthermore, it provides more design freedom [2]. Wire arc additive manufacturing (WAAM) is a variant of AM which is based on welding processes such as metal inert/active gas (MIG/MAG), tungsten inert gas (TIG) and plasma welding (PW) [3]. Among various AM processes, WAAM steps forward with its high deposition rate and low equipment cost as compared to the powder feed and laser/electron beam heated processes [4]. Cold metal transfer (CMT) which is a modified MIG variant relies on controlled dip transfer mode mechanism. It has been widely implemented for WAAM processes, due to its high deposition rate, low heat input and high bead quality production nearly without spatter [2, 5]. In addition, coaxial wire feeding compared to TIG and plasma processes provides simplicity for the deposition head motion [4].

WAAM parts have been produced so far from different materials such as Ti6Al4V [6, 7], Inconel [8], aluminum [9], nickel aluminum bronze [10], carbon [11] and stainless steels [12, 13] with comparable mechanical properties to the parts produced by conventional methods. The commercially available welding wire ER120S-G is a member of low-alloyed high strength steels family. It is commonly used to weld HY80 or HY100 steel in accordance with MIL-S-16216 [14]. So far, this material has not been reported in the literature regarding to WAAM process. High strength parts which have similar mechanical properties with ER120S-G can be produced with WAAM instead of casting, forging and rolling. In this paper, WAAM process with robotic CMT technology was applied to depositing the ER120S-G. The process parameters and building strategies were investigated and correlated with the geometrical and mechanical properties. Mechanical performance was also compared with high strength wrought and casting steels.

2. Experimental procedure

2.1 Materials

In the experiments, hot rolled structural mild steel S355 was used as a substrate. To ensure the repeatable and steady state welding conditions, the substrates were polished and then cleaned with ethanol. The 1.2 mm diameter wire material ER120S-G according to AWS A5.28 was used as welding wire. This material is a low alloy high strength steel which is commonly used for large vehicle, crane and high strength pressure vessel manufacturing.

The chemical composition of the wire is shown in Tab. 1.
In the experiments, a shielding gas mixture with 20% CO₂ and 80% Ar (M21) was used.

| Table 1. Chemical composition of the welding wire ER120S-G (producer data sheet) |
|--------------------------------------|
| Alloying Element (Legirajući element) | C | Mn | Si | Ni | Cr | Mo | Fe |
| % Wt. (Težinski %)                 | 0.09 | 1.82 | 0.89 | 2.03 | 0.25 | 0.64 | Balans |

2.2 Experimental Setup

Fig. 1 shows the experimental setup of CMT-WAAM system used in the experiments. The motion system is a 6-axis KUKA KR30 HA robot arm. The ‘Fronius TPS400i’ with CMT welding process is used as a welding power supply. The depositing speed and weld path were controlled by robot, while other parameters, such as voltage and current, were controlled with CMT power supply by selecting the wire feed speed. The CMT torch was fixed on the robotic arm and hold vertical to the substrate during the deposition.

![Figure 1. Experimental setup of the CMT-WAAM System](image)

2.3 Weld Bead Deposition

In the first stage of the experiments, single weld beads were deposited to investigate the influences of process parameters on bead dimensions. In all experiments, shielding gas type, mixture, gas flow rate, wire diameter, contact tip to work distance (CTWD) were constant parameters as listed in Tab 2.

| Table 2. Constant process parameters |
|--------------------------------------|
| Shielding Gas Zaštitni gas | 15 | 1.2 | 13 |
| Gas Flow Rate Protok gasa (l/min) | | | |
| Wire Diameter Prečnik žice (mm) | | | |
| CTWD (mm) | | | |
The WFS and WFS/TS were selected as variable process parameters. During the experiments WFS/TS was held constant to ensure the good weld bead quality by avoiding irregular combinations of welding parameters. For example, high TS with low WFS leads to humping effect. The average current varies linearly with the WFS, so that heat input equation (1) includes WFS/TS ratio and constant WFS/TS also provide to hold heat input (HI) constant.

\[
HI (\frac{J}{mm}) = \frac{V(t) \times Current(A)}{TS(\frac{m}{min})} \times \eta \times 0.06
\]  

(1)

Where voltage and current are the average values were read from the welding power supply measurements.

TS is the travel speed of welding torch. η is the efficiency of CMT welding process and set as 0.9 throughout this work. 0.06 value is used with unit conversion purpose.

Constant WFS/TS also provide to hold deposited material per unit length constant. Deposited material volume (DMV) per unit length equation (2) shows this relationship.

\[
DMV(\frac{mm^3}{mm}) = \frac{A(mm^2) \times WFS(\frac{mm}{sec})}{TS(\frac{mm}{min})}
\]  

(2)

Where A is the cross-sectional area of wire. Three different WFS/TS ratios which define low, medium and high heat input and six different WFS value were set in the experiment as listed in Tab 3.

| Heat Input Group | WFS/TS | WFS (m/min) |
|------------------|--------|-------------|
| Grupa prema unosu toplote | 1 | 5-7-8-9-10 |
|                  | 2 |              |
|                  | 3 |              |
The plates were sectioned from the middle. The sectioned surfaces were polished and etched as shown in Fig. 3a. The bead dimensions such as weld width, height, penetration, penetration area and reinforcement area were measured under Nikon SMZ745T stereo microscope as shown in Fig. 3b.

2.4 Multilayer Wall Geometry Deposition
In the second stage of the experiments, 250 mm length in x direction wall geometries were deposited. Two of the walls were 130 mm height single bead walls with deposition strategy as shown in Fig. 4a. The bidirectional deposition strategy for all depositions were applied not to have buildup at the start of path and a decreased of material at the end [15]. The single bead walls were built with the parameter of weld bead two which is in low heat input group as listed in Tab 4, while the second wall

2.4 Višeslojno deponovanje
U drugoj fazi eksperimenta, deponovano je 250 mm vara u x - pravcu. Dva sloja su bili visoki 130 mm sa strategijom izrade prikazanom na slici 4a. Strategije izrade u dva pravca za sva deponovanje su urađene tako da nema gomilanja materijala na početku putanja i smanjenu količinu materijala na kraju [15]. Pojedinačni navari su izrađeni sa parametrima koji odgovaraju grupi niskih unosa toplote, kao što je prikazano u tabeli 4, dok je u
were built with higher heat input by using the parameter of weld bead number eighteen.

The other two walls were deposited with adjacent multiple beads, with parallel and oscillation building strategies and weld bead two parameters as shown in Fig. 4b and 4c respectively. The step over distance between the adjacent beads was selected as 3 mm during the deposition. Tab. 4 shows the process parameters which were used during the deposition of the wall samples. After each layer a delay time (Tab. 4) was waited for not to have a flow and collapse of the wall. The average current and voltage values were measured and collected by welding power supply.

Table 4. Wall Deposition Process Parameters

| Sample Uzorak                        | WFS/TS | WFS (m/min) | I (A) | U (v) | Delay Time Pauza (min) |
|--------------------------------------|--------|-------------|-------|-------|------------------------|
| Single Bead Low Heat (SBLH)          | 10     | 6           | 195   | 17,4  | 1                      |
| Pojedinačni navar, niska toplota (SBLH) |        |             |       |       |                        |
| Single Bead High Heat (SBHH)         | 20     | 10          | 293   | 15,9  | 1                      |
| Pojedinačni navar, visoka toplota    |        |             |       |       |                        |
| Multiple Bead Parallel (MBP)         | 10     | 6           | 211   | 17,0  | 5                      |
| Višestruki navar, Paralelni (MBP)    |        |             |       |       |                        |
| Multiple Bead Oscillation (MBO)      | 10     | 6           | 215   | 16,8  | 5                      |
| Višestruki navar, Oscilujući (MBO)   |        |             |       |       |                        |

The deposited single bead low heat (SBLH), single bead high heat (SBHH), multiple bead parallel...
(MBP) and multiple bead oscillation (MBO) walls are shown in Fig. 5. Single bead low (Fig. 5a) and high heat input (Fig. 5b) walls were deposited as 70 and 62 layers respectively. Multiple bead parallel and oscillation walls were deposited as 22 layers and 9 layers respectively.

Figure 5. Deposited wall geometries
Slika 5. Geometrije deponovanih slojeva

2.5 Mechanical Property Analysis
Horizontal and vertical oriented tensile test specimens were extracted from two single bead walls as shown in Fig. 6a. The specimen dimensions were defined according to ASTM E8/E8M standards as shown in Fig. 6b. The tensile tests were performed with Zwick Z250 testing machine according to EN ISO 6892-1.

Figure 6. Specimen orientation on walls (a), tensile specimen size in mm (b)
Slika 6. Orientacija epruveta (a), epruveta za zatezanje, dimenzije u mm (b)
3. Results and discussion
3.1 Weld Bead Deposition
Heat input decreases with WFS slightly at constant WFS/TS as shown in Fig. 7a. It proves that the heat input can be controlled with a constant WFS/TS. Additionally, with an increasing WFS/TS ratio, the heat input shifts to another heat input group, when WFS is held constant. Bead width variation is similar to heat input as shown in Fig. 7b. It shows that heat input has a great effect on bead width.

Fig. 7. a) Heat input during bead deposition b) Bead widths
Slika 7. a) Unos toplote tokom deponovanja navara, b) širine navara

Fig. 8a shows that bead height increases with WFS/TS, but it does not change significantly with WFS at constant WFS/TS. Total weld area variation is also very similar with heat input variation (Fig. 7a) as shown in Fig. 8b. It proves that bead cross section area can be controlled with heat input.

Fig. 8. a) Bead height b) Total weld area
Slika 8. a) Visina navara b) Ukupna površina navara

3.2 Tensile Tests
Tensile test results obtained from horizontal samples are shown in Fig. 9. The strength values decrease from bottom to the middle section specimens, due to the heat accumulation and decreasing cooling rate. Single bead low heat wall horizontal (LHH) samples have higher strength values compared to high heat input wall horizontal (HHH) samples, due to different heat input and cooling rates between the walls. Both tensile and...
yield strength of the specimens which are extracted from the same locations show a similar yield strength of the specimens which are extracted from the same locations show a similar trend between the walls. The reason can be attributed that both walls are built with same building strategy.

The vertical oriented specimen strength values shown in Fig. 10 exhibit a different trend than horizontal specimens, due to the anisotropy. More heat input and lower cooling rates also lead to decrease the strength like horizontal specimens. The trends of low and high heat input wall sample tensile and yield strength curves are also similar as in horizontal samples.

The average tensile strength values (975 MPa) of the vertical and horizontal oriented specimens from low (LHH, LHV) and high heat input (HHH, HHV) walls were compared with S690Q structural high strength and G24Mn6+QT2 casting steel as shown in Fig. 11. It can be seen that, tensile and yield strength of G24Mn6 were reached without any heat treatment. S690Q structural steel yield strength could not be reached, but very close to it with 640 MPa, on the other hand tensile strength are highly compared to it. Average strength of horizontal specimens is greater than vertical ones, since the grain boundaries in z direction strengthens the part.

Vrednosti dobijene za vertikalne epruvete koje su prikazane na slici 10 su pokazale drugačiji trend u odnosu na horizontalne, usled anizotropije. Veći unos toplote i kraće vreme hlađenja su takođe doveli do smanjene čvrstoće kao i kod horizontalnih epruveta. Ponašanje zateznih osobina kod niskog i visokog unos toplote kod horizontalnih epruveta u pogledu krivi zatezanja je takođe bilo slično.

Prosečna vrednost zatezne čvrstoće (975 MPa) vertikalno i horizontalno orijentisanih epruveta sa niskim (LHH i LHV) i visokim unosom toplote (HHH, HHV) su upoređene sa konstrukcionim čelikom povišene čvrstoće S690Q i livenim čelikom G24Mn6+QT2, slika 11. Može se videti da su granica tečenja i zatezna čvrstoća čelika G24Mn6+QT2 dostignute bez potrebe za termičkom obradom. Što se čelika S690Q tiče, njegove mehaničke osobine nisu dostignute, ali su bile veoma bliske, sa granicom od 640 MPa, dok je sa druge strane zatezna čvrstoća bila nešto viša. Prosečna čvrstoća horizontalnih epruveta je veća u
The standard deviations of horizontal specimens have more than the vertical ones, since the anisotropy in z direction is more than in x direction. Poređenju sa vertikalnim, s obzirom da granice zrna u z-pravcu ojačavaju taj deo. Standardna devijacija horizontalnih epruveta je bila izraženija nego kod vertikalnih, usled anizotropije, za razliku od x-pravca.

Figure 11. Average strength of the specimens and reference materials
Slika 11. prosečna čvrstoća epruveta u poređenju sa referentnim materijalima

The minimum average elongation obtained from the specimens is 14%, as shown in Fig. 12, so that S690Q elongation requirement is fulfilled. This value is also so close to G4Mn6 elongation requirement. Low heat input wall has better elongation results in both specimen orientations compared to high heat input.

Minimalno srednje izduženje je dobijeno za epruvete iznosi 14%, kao što se vidi na slici 12, što znači da su dostignute vrednosti kao kod materijala S690Q. Ova vrednost je takođe bliska izduženju kod G24Mn6+QT2 čelika. Niski unos toplote je dao bolje rezultate u pogledu izduženja, za obe orijentacije epruveta u poređenju sa visokim unosom toplote.

Figure 12. Elongation of the specimens and reference materials
Slika 12. Izduženje epruveta i referentnih materijala
4. Conclusions
High strength low alloy steel parts were fabricated by CMT robotic WAAM system with different process parameters and building strategies. Effects to mechanical properties were investigated. Additionally, mechanical performance was compared with high strength wrought and casting steels. The following conclusions can be drawn:

Single Beads:
- Single weld beads showed a good quality with WFS (5-10 m/min) and WFS/TS (10-15-20) process parameters.
- WFS/TS is the major parameter to control the heat input.
- Heat input correlates well with the weld width and cross-sectional area.
- Bead width, height, penetration and cross-sectional area increase with an increasing WFS/TS.

Multiple Bead Walls:
- Yield and tensile strength of horizontal specimens extracted from SBL and SBH walls had higher value than vertical ones.
- SBL wall specimens had higher average tensile and yield strength values than SBH walls.
- Mechanical properties of parts produced with high strength steel wire can be compared to G24Mn6+QT2 casting steel, except slight elongation difference. Tensile strength and elongation were fulfilled for S690Q and yield strength is very close to the reference value.

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References
[1] "Standard Terminology for Additive Manufacturing Technologies," F2792-12a, ASTM, 2015.
[2] S. W. Williams, F. Martina, A. C. Addison, J. Ding, G. Pardal and P. Colegrove, "Wire + Arc Additive Manufacturing," Materials Science and Technology, 2016.
[3] S. Rios, P. A. Colegrove, F. Martina and S. W. Williams, "Analytical process model for wire + arc additive manufacturing," Additive Manufacturing, 2018.

4. Zaključci
Delovi od niskolegiranog čelika povišene čvrstoće su proizvedeni primenom robotizovane CMT WAAM metode sa različitim parametrima procesa i strategijama izrade. Ispitani su uticaji na njihove mehaničke osobine. Uz to, njihovo ponašanje je upoređeno sa kovanim i livenim čelicima povišene čvrstoće. Na osnovu toga su izvučeni sledeći zaključci:

Za pojedinačne navare
- Pojedinačni navari su pokazali dobar kvalitet za procesne parametre WFS u rasponu 5-10 m/min i WFS/TS od 10-15-20.
- WFS/TS je parametar koji u najvećoj meri kontroliše unos toplote.
- Unos toplote je pokazao dobru korelaciju sa širinom navara i površinom poprečnog preseka.
- Širina navara, visina, uvarivanje i površina poprečnog preseka rastu sa povećanjem odnosa WFS/TS.

Višestruki navari:
- Granica tečenja i zatezna čvrstoća horizontalnih epruveta izvađenih iz SBL i SBH zidova su bile veće u odnosu na vertikalne epruvete.
- SBL epruvete su imale veće srednje vrednosti zatezne čvrstoće i granice tečenja u poređenju sa SBH epruvetama.
- Mechanical properties of parts produced with high strength steel wire can be compared to G24Mn6+QT2 casting steel, except slight elongation difference. Tensile strength and elongation were fulfilled for S690Q and yield strength is very close to the reference value.

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References
[4] X. Xu, J. Ding, S. Ganguly, C. Diao and S. Williams, "Preliminary Investigation of Building Strategies of Maraging Steel Bulk Material Using Wire+Arc Additive Manufacture,“ Journal of Materials Engineering and Performance, pp. 1-7, 17 7 2018.
[5] D. Ding, Z. Pan, D. Cuiuri and H. Li, Wire-feed additive manufacturing of metal components: technologies, developments and future interests, 2015.
[6] B. Baufeld, "Effect of deposition parameters on mechanical properties of shaped metal deposition parts," in Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2012.
[7] F. Wang, S. Williams, P. Colegrove and A. A. Antonysamy, "Microstructure and mechanical properties of wire and arc additive manufactured Ti6Al4V," Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 2013.
[8] B. Baufeld, "Mechanical properties of INCONEL 718 parts manufactured by shaped metal deposition (SMD)," Journal of Materials Engineering and Performance, 2012.
[9] K. S. Derekar, A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium, 2018.
[10] D. Ding, Z. Pan, S. van Duin, H. Li and C. Shen, "Fabricating superior NiAl bronze components through wire arc additive manufacturing," Materials, 2016.
[11] P. A. Colegrove, H. E. Coules, J. Fairman, F. Martina, T. Kashoob, H. Mamash and L. D. Cozzolino, "Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling," Journal of Materials Processing Technology, 2013.
[12] T. Skiba, B. Baufeld and O. v. d. Biest, "Microstructure and Mechanical Properties of Stainless Steel Component Manufactured by Shaped Metal Deposition," ISIJ International, vol. 49, no. 10, pp. 1588-1591, 2009.
[13] O. Yilmaz and A. A. Ugla, "Microstructure characterization of SS308LSi components manufactured by GTAW-based additive manufacturing: shaped metal deposition using pulsed current arc," International Journal of Advanced Manufacturing Technology, 2017.
[14] "Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding," 2003.
[15] Y. M. Zhang, Y. Chen, P. Li and A. T. Male, "Weld deposition-based rapid prototyping: A preliminary study," Journal of Materials Processing Technology, vol. 135, no. 2-3 SPEC., pp. 347-357, 2003.