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The influence of technological parameters on the structure formation of aluminum alloys during direct deposition of wire

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Abstract. The paper presents the results of an investigation of application arc, laser and laser-arc sources for process direct deposition of aluminum wire. Experimental studies have focused on the determination mode of parameters to provide uniform formation of a thin wall during successive layering. The metallographic analysis of cross-sections of the samples was performed. The microhardness, chemical and mechanical tests were carried out.

1. Introduction

Research and development of additive technologies (AT) focused on the manufacture of complex-shape metal components, the production of which with using traditional methods is economically disadvantageous [1-5]. The main research in the field of AT are directed on the methods based on the powder-feed/-bed with using the power source of laser or electron beam [6-10]. The deposition rate of the detail does not exceed 25 gmin⁻¹ [11]. It limits the application of the method with using of powder for production large-size metal components. For large-sized products the most effective deposition methods is methods that based on using wire as building material [12-13]. The use of wire reduce costs from expense decrease the usage and cost of materials. In addition, the process of deposition from wire is more environmentally safe [14]. Due to their high specific strength and good corrosion resistance, large-size products made from aluminum alloys are widely used in the automotive, aerospace and railway industries. Now, there are row of studies focused at research on wire arc additive technology [15-17]. Arc of melting and non-melting electrode, laser radiation, electron beam are used as energy source for deposition process.

This paper presents the results of a comparison of the processes of direct deposition of aluminum wire with using arc, laser and laser-arc sources.
2. Equipment and materials

Ytterbium fiber laser LS-16 used as a source of laser radiation, with a maximal output power of 16 kW. The radiation was transported via a fiber cable to the optical welding head of the laser-arc module. The welding head HIGHYAG BIMO with focus distance 460 mm and spot diameter of 0.2 mm in the focal point used for focusing laser radiation on the surface of samples [18]. EWM Taurus 551 Synergic S FDW used as a source of arc. The wire feeders PDGO – 601 (ITW) and Taurus Synergic S drive 4L (EWM) used for transfer wire to work zone of process. In the experiments, plates from aluminum alloy of 16mm thickness were used as substrate and wire AlMg6 of 1.2 mm in diameter as filler material. The linear walls were built-up from the wire on the plate by successively overlaying layers with using arc, laser and laser-arc methods. Argon was used as shielding gas.

Metallographic studies were performed at an optical microscope company LOMO METAM LV-31 with a camera MS-6.3. Chemical analysis was performed using scanning electron microscope PhenomProX. The microhardness tests were carried out at microhardness tester FM-310 (Future – Tech corporation) with software Thixomet at a test load of 500 g and step between the measurement points of 1000 microns. Mechanical tests were carried out on the universal tensile testing machine Zwick/Roell Z100. Maximum tensile/compressive force-100 kN.

3. Experimental procedure

The wire was fed by feeder at an angle to the surface of substrate to the zone of laser radiation or welding arc combustion. By melting, it formed a deposited layer. The experiments on the deposition of single layers to investigate the influence of process parameters on the shape of layer were made. Process variables are shown in table 1.

| Variables                                      | Arc deposition | Laser deposition | Laser-arc deposition |
|-----------------------------------------------|----------------|------------------|---------------------|
| Laser head angle, °                           | -              | 15               | 15                  |
| Laser power, (kW)                             | -              | 1.5-7.5          | 4-6                 |
| Diameter of the laser beam spot, (mm)         | -              | 2.3-4.8          | 0.2-2.3             |
| Wire feeder                                    | Taurus         | PDGO – 601       | Taurus              |
| Wire feed angle, (°)                          | 60-90          | 35-40            | 90                  |
| Stick-out distance of wire, (mm)              | 10             | 10               | 10                  |
| Distance between the axis of the laser beam and the central axis of the wire, (mm) | -              | 1-2              | 0-1                 |
| Wire feed speed, (m min⁻¹)                    | 3-15.6         | 0.5-7            | 3-7.5               |
| Deposition rate, (mm s⁻¹)                     | 10-60          | 5-40             | 7-30                |
| The pause time between passes, (min)          | 1-3            | 8-15             | <1                  |

After visual inspection of the appearance of deposited single layers and metallographic studies of cross-sections, process variables for deposition of thin walls were selected. The minimum penetration of the substrate, stable formation of the layer, the minimum width of the layer were selected as criteria for the choice of process variables. The deposition of thin walls was carried out with successively overlaying layers. Step of vertical motion was according to the height of the previous layer, measured after the end of each pass. During deposition, argon was fed through the welding torch and/or through additional nozzles to protect the welding pool and the deposited layer. The gap between the nozzles and the surface of substrate was 2-4 mm. In the course of metallographic studies of cross-sections, the
existence of defects, chemical composition and microstructure were determined. The samples were etched in a 7% solution of hydrofluoric acid (HF) for preparation of microstructure. The microhardness and mechanical static tensile tests of the deposited samples were carried out.

4. Results and discussion
At the deposition of single layers was investigate the influence of the deposition rate, wire feed speed and laser power on the shape of layer. The results are shown in figure 1.

(a)

(b)
Figure 1. The results of experiments of the deposition of single layers: (a) arc deposition; (b) laser deposition; (c) laser-arc deposition.

Figure 1a shows that at low deposition rates (<10 mms⁻¹) and the average wire feed rate (< 7 mmin⁻¹), the arc deposition process does not proceed due to unstable arcing. At high deposition rates (> 40 mms⁻¹), the formation of the layer is unstable, not enough filler material; it requires an increase of wire feed speed. Uniform stable formation of the layer begins at a wire feed speed of 9.6 mmin⁻¹. Further increase of the wire feed speed causes an increase the depth penetration of the substrate and leads to the formation of layer with undercuts. Increasing of the deposition rate reduces the stability of the process. Selected modes for arc deposition of thin wall: deposition rate of 20 and 40 mms⁻¹, wire feed speed of 9.6 mmin⁻¹.

Figure 1b shows that the laser deposition process with stable formation of layer begins at a laser power of 4.5 kW. Further increase of power causes an increase width of layer and the depth penetration of the substrate while reducing the layer height. In this case, the linear energy for the laser deposition was higher than for arc deposition, it can be explained by large losses of energy in the reflection. From the figure 1b also it can be seen that the process of stable formation begins at a wire feed speed of 3 mmin⁻¹. Further increase of the wire feed speed causes an increase of the height of layer and the fluctuation of the depth penetration of substrate. With too high a wire feed speed (7 mmin⁻¹), the used laser radiation power is not enough for its stable melting and layer formation. In this case, the wire feed speed provides a stable layer formation, for this process is less than in the case of arc deposition. Selected modes for laser deposition of thin wall: diameter of the laser beam spot of 4.2 mm; laser power of 4.5 kW; wire feed speed of 3 mmin⁻¹; deposition rate of 20 mms⁻¹. During metallographic studies have not detected the presence of large pores in single layers.
Figure 1c shows that the variation range of laser power, providing uniform formation of a single layer by laser-arc method is wider than at the laser deposition. The laser power of 5 kW was selected. In the course of experiments of deposition single layers, it was also found, that the stable formation of a smooth layer is at deposition rate comparable or lower than for laser deposition (15-20 mms\(^{-1}\)). Selected modes for laser-arc deposition of thin wall: diameter of the laser beam spot of 2.3 mm; the laser power of 5 kW; wire feed speed of 7 mmm\(^{-1}\); deposition rate of 20 mms\(^{-1}\). According to the method described in section 3, samples of thin walls were built-up at the selected mode of parameters. The appearance of the samples obtained by arc, laser and laser-arc deposition is shown in figures 2, 3 and 4, respectively.

**Figure 2.** The image of the thin walls built-up by arc method:

(a) wire feed speed is 9.6 mmm\(^{-1}\), deposition rate is 20 mms\(^{-1}\), step of vertical motion is 1.5 mm, number of passages is 42, width of wall is 7.8 mm, the wall height is 40 mm, the average layer height is 0.95 mm (b) wire feed speed of 9.6 - 11.6 mms\(^{-1}\), deposition rate is 40 mms\(^{-1}\), step of vertical motion is 0.7-1.2 mm, number of passes is 60, width of wall is 6 mm, the wall height is 38 mm, the average layer height is 0.63 mm.

**Figure 3.** The image of the thin wall built-up by laser method:

wire feed speed is 3 mmm\(^{-1}\), deposition rate is 20 mms\(^{-1}\), laser power is 4.5 kW, diameter of the laser beam spot is 4.2 mm, step of vertical motion is 0.5-0.9 mm, number of passages is 44, width of wall is 6 mm, the wall height is 23 mm, the average layer height is 0.52 mm.
Figure 4. The image of the thin wall built-up by laser-arc method:

wire feed speed is 7 mmin$^{-1}$, deposition rate is 20 mms$^{-1}$, laser power is 5 kW, diameter of the laser beam spot is 2.3 mm, step of vertical motion is 0.8-1.3 mm, number of passes is 46, the width of wall is 6.4 mm, the wall height is 50 mm, the average layer height is 1.08 mm.

From figures 2-4, it can be seen that the arc method at the same deposition rate is characterized by maximum productivity and the width of wall, but the worst among all the roughness of the side surface. The wall, built-up by laser method, is the most uniform vertically and along the length, but it is characterized by the lowest productivity. The laser-arc method has intermediate position in terms of productivity, with the average layer height more than 1 mm and with the width of wall of about 6 mm.

5. Metallographic studies and microhardness tests

Porosity for two variants of the mode parameters of arc deposition has been identified during the research of the macrostructure of thin wall samples (see figure 5).

Figure 5. Macrostructure of thin wall samples built-up by arc method: (a) deposition rate is 20 mms$^{-1}$; (b) deposition rate is 40 mms$^{-1}$.

The sample built-up at a deposition rate of 20 mms$^{-1}$ had pores with a maximum size up to 120 µm, while the sample built-up at 40 mms$^{-1}$ had the maximum pore size of 160 µm. For further researches, a sample with the smallest pore size was selected, it built-up at the deposition rate of 20 mms$^{-1}$ and wire feed speed of 9.6 mmin$^{-1}$. 
During the research of the microstructure, the lamellar mesostructure was found in the samples for all methods (figure 6). The epitaxial increasing of grain size through the layers in the direction of the deposition layers was detected during process of built-up from the wire. The chemical analysis of the wire and walls built-up by various methods was carried out. In the photos from the scanning electron microscope it was found that the microstructure of the samples built-up by all methods consists of an aluminum matrix with $\text{AL}_3(\text{Fe}, \text{Mn})$ phase inclusions. When deposition chemical and phase composition of the base material does not change. The concentration of Mg in the matrix of samples obtained by arc, laser and laser-arc methods is approximately 6 % that corresponds to the concentration of it in the wire. It should be note that the morphology of inclusions with a high content of iron and manganese varies. During deposition inclusions stretched in the built-up direction.

![Figure 6. The microstructure of samples made of aluminum wire AlMg6Zr: (a) arc deposition; (b) laser deposition; (c) laser-arc deposition.](image)

The results of microhardness tests are shown in figure 7. Microhardness was measured in different areas of the sample, in direction from the substrate to the top of wall. Measurements were carried out in layers and at layer boundaries.

![Figure 7. The results of microhardness tests: (a) Scheme of measurements of microhardness; (b) Graph of distribution of microhardness.](image)
Samples built-up with laser and arc methods are characterized by a uniform distribution of microhardness along the built-up direction. Figure 7b shows that the value of microhardness of the sample built-up by the laser method is higher than for arc method. For the laser method, it is about 80 HV, for the arc about 60-65 HV. The standard hardness for AlMg6 alloy is 70 HV. The sample built-up by the laser-arc method is characterized by non-uniform distribution of microhardness: the fusion zone of the layers is harder than the middle part of the layer by about 10 HV. The average value coincides with the microhardness of the sample built-up by the laser method.

The technology of laser-arc direct deposition allows increasing productivity compared to the laser method; reduce porosity and improve the quality of the side surface compared to the arc method. The arc is stabilized by laser radiation during laser-arc deposition. It causes the formation of a wall with less roughness of surface than at the arc method. Also occurs a small increase of the width of layer compared to the laser method.

6. Mechanical tests

Samples for static tensile testing were cut from the walls built-up by laser-arc and arc methods. Tensile test was carried out in the direction along the layers. The scheme of cutting samples for mechanical tests is shown in figure 8.

The best results of mechanical tests are obtained for the laser-arc deposition method. The value of the ultimate tensile strength of the sample was 296 MPa, it is similar to the value characteristic for the plate material of alloy AlMg6 (315 MPa). The value of ultimate tensile strength for sample of arc deposition was 268 MPa. This difference can be caused by different cooling rates of the layers due to the difference in heat sources.

Conclusion
- The results showed the possibility of built-up of the walls of aluminum wire with successively overlaying layers by arc, laser and laser-arc methods.
- The arc method is characterized by increased porosity and roughness of the side surface in comparison with laser and laser-arc methods.
- There is a difference in the microhardness of samples built-up by different methods (uniformity of microhardness in cross-section for laser deposition, a greater value of microhardness and irregularity in cross-section for laser-arc deposition method).
- The Mg content in all built-up samples corresponds to its content in the filler wire.
- It is shown that the laser-arc method is the most productive.
- Samples built-up by laser-arc method have a more strength compared to its by other methods.
References

[1] Frazier W E 2014 Metal Additive Manufacturing: A Review *J. of Mat. Engin. and Perf.* **23** pp 1917–1928

[2] Gu D, Meiners W, Wissenbach K, Poprawe R 2012 Laser additive manufacturing of metallic components: materials processes and mechanisms *International Materials Reviews* **57** Iss. 3 pp 133-164

[3] Kenel C, Dasargyri G, Bauer G, Colella T, Spiereings A, Leinenbach A B, Wegener C 2017 Selective laser melting of an oxide dispersion strengthened (ODS) γ-TiAl alloy towards production of complex structures *Materials and Design* **134** pp 81–90

[4] Rauch E, Unterhofer M, Dallasega P 2017 Industry sector analysis for the application of additive manufacturing in smart and distributed manufacturing systems *Manufacturing Letters* **56** pp 43-48

[5] Deb Roy T, Wei H L., , Zuback J S, Mukherjee T, Elmer J W, Milewski J O, Beese A M, Wilson-Heid A, De A, Zhang W 2018 Additive manufacturing of metallic components – Process, structure and properties *Progress in Materials Science* **92** pp 112–224

[6] Dutta B, Palaniswamy S, Choi J, Song L J, Mazumder J 2011 Additive manufacturing by direct metal deposition *Advanced Materials & Processing* **169** pp 33-36

[7] Lawrence Murr E, Amato E M K N, Gaytan S M, Hernandez J, Ramirez D A, Shindo P W, Wicker F M R B 2012 Fabrication of Metal and Alloy Components by Additive Manufacturing: Examples of 3D Materials Science *Journal of Materials Research and Technology* **1** Iss. 1 pp 42-54

[8] Zerbst U, Hilgenberg K 2017 Damage development and damage tolerance of structures manufactured by selective laser melting – a review *Procedia Structural Integrity* **7** pp 141-148

[9] Nguyen Q B, Nai M L S, Zhu Z, Sun Ch-N, Zhou J W W 2017 Characteristics of Inconel Powders for Powder-Bed Additive Manufacturing *Engineering* **3** Iss 5 pp 695-700

[10] Baufeld B, Brandl E, van der Biest O 2011 Wire based additive layer manufacturing: Comparison of microstructure and mechanical properties of Ti–6Al–4V components fabricated by laser-beam deposition and shaped metal deposition *Journal of Materials Processing Technology* **21** pp 1146-1158

[11] Matilainen V, Piili H, Salminena A, Syvänenc T, Nyrhilä O 2014 Characterization of Process Efficiency Improvement in Laser Additive Manufacturing *Physics Procedia* **56** pp 317 – 326

[12] Brand E, Michailov V, Viehweger B, Leyens Ch 2011 Deposition of Ti–6Al–4V using laser and wire, part II: Hardness and dimensions of single beads *Surface & Coatings Technology* **206** pp 1130-1141

[13] Zhang Ch, Li Yu, 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 & Engineering A* **711** pp 415–423

[14] Ding D, Pan Z, Cuiuri D, Li H 2015 Wire-feed additive manufacturing of metal components: technologies, developments and future interests *International Journal of Advanced Manufacturing Technology* **81** pp 465-481

[15] Silva C M A, Bragança I M F, Cabrita A, Quintino L 2017 Formability of a wire arc deposited aluminum alloy *Martins Journal of the Brazilian Society of Mechanical Sciences and Engineering* **216** pp 134-149

[16] Gu J, Ding J, Williams SW, Gu H, Ma P, Zhai Y 2016 The effect of inter-layer cold working and post-deposition heat treatment on porosity in additively manufactured aluminum alloys *Journal of Materials Processing Technology* **230** pp 26-34

[17] Gu J, Ding J, Williams SW, Gu H, Bai J, Zhai Y, Ma P 2016 The strengthening effect of inter-layer cold working and post-deposition heat treatment on the additively manufactured Al–6.3 Cu alloy *Materials Science and Engineering: A* **651** pp 18-26

[18] Turichin G A, Tsibulsksiy I A, Kuznetsov M V 2012 Distribution of magnesium in the weld metal during laser-arc welding of aluminum-magnesium alloys *Scientific and technical statements of SPbSPU. Economic sciences* **4** pp 156-159