The influence of technological parameters on the structure formation of copper-nickel alloys during direct deposition of wire

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Abstract. The technology of layer-by-layer deposition is the most relevant for the manufacture and repair of products, due to the least time and resource costs compared to traditional manufacturing technologies. In the same time, application of wire instead of powder, allows to reduce consumption of filler material and increase production efficiency.

In this regard, research was carried out on the influence of the parameters on the wire deposition process to form thin walls of copper-nickel alloys using a laser and arc method. For the wire deposition of copper-nickel walls, CuNi6 wire was used. Experimental work was carried out on the technological complex, based on the fiber laser power up to 16 kW and the arc source for MIG welding. The report presents samples of deposition walls, investigated alloys obtained for both deposition methods at various technological parameters. Metallographic studies of the samples were performed, microhardness was measured, and a comparative analysis of laser and arc deposition methods.

1. Introduction

The additive manufacturing (AM) over last decades are receiving increasing expansion in different branch of industry [1]. Automotive [2], aerospace [3], medical, food and other industries are interested in applying of AM, which allowing to get quality production, increasing productivity and reducing the cost of production due to material savings [4, 5]. The technology is based on the possibility of obtaining products of simple and complicated forms with massive or small size from different materials layer-by-layer way.

Among the methods of obtaining metal products, the main technologies are direct layer-by-layer deposition from a powder [6, 7] or wire under the influence of various energy sources (electron beam,
laser, arc, etc.). At deposition massive products, the advantages are on the side of deposition from wire, because of the higher process speed, less negative material consumption, less raw material costs and environmental compared to the powder method.

The article is focused on processes of laser and electric arc (GMAW) deposition from wire. The use of the arc method is distinguished by the low cost of welding equipment and consumables. However, at the laser method is lower heat input, which reduces tensions and deformations. This makes it possible to obtain a more precise shape of the product and reduce operations for further machining.

Despite the difference in materials from which products are produced, there are common problems that are intensively studied, regardless of the energy source used: the formation of the depositing layer [8-11], the processes of droplet transfer of the metal wire [12], and the overlapping of the deposited layers [13]. In some works, different methods of wire deposition are compared [14-16].

However, despite a lot of researches, the process of deposition from wire for copper alloys remains unexplored. In this paper are presented the results of compare direct deposition of products from copper-nickel wire using laser and electric arc sources. In the course of the work, studies were performed on the selection of optimal regimes for the two methods.

2. Experimental design
The purpose of the experiments was to investigate the technological possibilities of deposition from a wire based on a copper-nickel alloy in two methods: laser and arc. Figure 1 shows the process scheme for each method. In both cases a plate of low-alloy steel was used for the substrate. In the method (1a), the wire was fed to the substrate at an angle of 60° from the vertical to zone of the defocused laser radiation (the diameter of the laser spot was 4 mm). In case arc (1b), arc torch was fixed vertically relative to the substrate. The wire CuNi6 of 1.2 mm in diameter was used in experiments (the chemical composition is shown in Table 1).

Ytterbium fiber laser LS-16 used as a source of laser radiation, with a maximal output power of 16 kW. The radiation was transported through 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. EWM Taurus 551 Synergic S FDW for MIG/MAG welding used as a source of arc. The wire feed mechanisms PDGO – 601 and Taurus Synergic S drive 4L used for transfer of the wire. Ar was used as protective gas with a flow rate of 25 l min⁻¹.

![Figure 1. Scheme of the process of deposition from wire using laser radiation (a), arc (b).](image-url)
Table 1. Chemical composition of CuNi6 wire.

| Alloys | Chemical Composition (wt %) |
|--------|-----------------------------|
|        | Fe  | Ni+Co | C   | Si  | Mn  | Ti  | Cu   | Pb   | Zn   |
| CuNi6  | 1-1.4 | 5-6.5  | 0.03 | 0.15-0.3 | 0.3-0.8 | 0.1-0.3 | 90-93.45 | < 0.005 | < 0.5 |

The study of the formation of single layers was the first part of the experiment. There was considered the influence on layer formation such process parameters as: wire feed rate, transfer speed, power of laser radiation. The process variables are shown in table 1. The next part of the experiment was to select the optimal modes of single layer deposition and the layer-by-layer way to get the wall. The finally part was to evaluate the quality of the wall, and to compare the results obtained by different methods.

Table 2. Process variables.

| Variables                           | Laser deposition | Arc deposition |
|-------------------------------------|------------------|----------------|
| Wire feed angle                     | 60°              | 90°            |
| Laser head angle                    | 15°              |                |
| Wire feeder                         | ПДГО – 601       | Taurus Synergic S drive 4L |
| Laser power (kW)                    | 4-8              |                |
| Wire feed speed (m min⁻¹)           | 5                | 1-3            |
| Deposition rate (mm s⁻¹)            | 20-40            | 7-40           |

The quality of the deposited layers was evaluated visually and on the base of metallographic analysis of cross-section. The defects and the microstructure of the samples were determined. The microhardness of the deposited samples was also measured.

3. Results and Discussion

Figure 2 shows the appearance of the single layers deposited by an arc method. The wire feed rate was set in the range of 1-3 m min⁻¹, for obtaining the lowest heat input. The transfer speed was 7 mm s⁻¹. The stable processes of arc burning and formation of the layer was observed with a maximum wire feed rate of 3 m min⁻¹; in other cases, the burning of the arc was not stable over the whole distance, or the formation of the layer was represented as single drops. It’s caused that was fixed a large-drop transfer of molten metal from the electrode.

![Figure 2. The appearance of single layers by arc deposition at transfer speed 7 mm s⁻¹: 1) Vw.f. = 1 m min⁻¹; 2) Vw.f. = 3 m min⁻¹; 3-4) Vw.f. = 2 m min⁻¹; 5) Vw.f. = 1.5 m min⁻¹; 6) Vw.f. = 1.3 m min⁻¹.](image)

The influence of transfer speed on layer form was evaluated in the range of 10-40 mm s⁻¹, at wire feed rate 4.5 m min⁻¹. Figure 3 shows the appearance of deposited layers. At all range of speed was observed stable burning of arc. The width of layers was remained practically unchanged, however, the form was changed visibly: as the process speed increased, the contact angle decreased (table 3).
Figure 3. The appearance of single layers by arc deposition at wire feed rate 4.5 m min\(^{-1}\): 7) \(V_{t,s.} = 10\) mm s\(^{-1}\); 8) \(V_{t,s.} = 15\) mm s\(^{-1}\); 9) \(V_{t,s.} = 20\) mm s\(^{-1}\); 10) \(V_{t,s.} = 25\) mm s\(^{-1}\); 11) \(V_{t,s.} = 30\) mm s\(^{-1}\); 12) \(V_{t,s.} = 40\) mm s\(^{-1}\).

At deposition of layers by the laser method, it’s necessary to provide steady melting of the wire and its conversion into a liquid bath during the whole process. Figure 4 shows the appearance of the single deposited layers which was obtained at studding of influence on layer form of parameters such as power of laser radiation and transfer speed. The wire feed rate was 5 m min\(^{-1}\). At low heat input until 260 J mm\(^{-1}\) (regime №13, 15, 17) the formation of steady layer was unstable or missing.

Figure 4. The appearance of single layers by laser deposition at \(V_{w,f.} = 5\) m min\(^{-1}\): 13) \(P = 8\) kWt; 40 mm s\(^{-1}\); 15) \(P = 8\) kWt; 30 mm s\(^{-1}\); 14) \(P = 8\) kWt; 20 mm s\(^{-1}\); 16) \(P = 6\) kWt; 20 mm s\(^{-1}\); 17) \(P = 4\) kWt; 20 mm s\(^{-1}\).

To evaluate the depth of melting of substrate, the presence of defects and the geometry of single layers obtained by both methods cross sections were made, which are shown on figure 5.
Figure 5. The cross sections of single layers deposited by arc (a) and laser (b) methods.

In case arc method, as increased of transfer speed from 10 mm s\(^{-1}\) to 40 mm s\(^{-1}\), the depth of melting of substrate and the contact angle decreased (table 3). At laser method was observed the same trend, however, values generally lower than those for the arc. At all cross sections are noted small pores with size up to 40 μm, that is probably due to a lack of shielding gas. The large defects are noted at regime №16 and №17, the reason of that unstable of the process at set parameters.

For deposition of linear walls by both methods were taken the maximum and the reduced transfer speed. For arc method were taken parameters of regimes №7, 12 (40 mm s\(^{-1}\) и 10 mm s\(^{-1}\)). The maximum and the reduced transfer speed for laser method were obtained at regimes №13, 14 (40 mm s\(^{-1}\) и 20 mm s\(^{-1}\)). However, the values of laser power were not enough for steady melting of wire at regimes №13, it were increased up to 10 kWt (№19). Also, to compare the walls, which were obtained at reduced speed by different methods, the wall was deposited by a laser method at a speed of 10 mm s\(^{-1}\) (№18: Pl = 6 kWt, Vw.f. = 2 m min\(^{-1}\)). In both cases at deposition of the wall, height was measured after each deposited layer and the height of the last layer was taken as the step.
Table 3. The values of the parameters of the melting depth and the contact angle.

| № regime | the melting depth (μm) | the contact angle |
|----------|------------------------|------------------|
| arc      |                        |                  |
| 2        | 228,3                  | 95,1             |
| 3        | 122,1                  | 82,9             |
| 4        | 79,5                   | 77,7             |
| 7        | 164,5                  | 82,6             |
| 8        | 138,3                  | 81,2             |
| 9        | 119,7                  | 53,3             |
| 10       | 137,2                  | 43,2             |
| 11       | 109,6                  | 51,4             |
| 12       | 97,9                   | 34,3             |
| laser    |                        |                  |
| 13       | 0                      | 33,8             |
| 14       | 96,2                   | 36,9             |
| 15       | 103,5                  | 49,8             |
| 16       | 49,2                   | 55,3             |
| 17       | 0                      | 61,6             |

In the case of the arc method, the further overlapping layers did not cause any changes in the stability of the process. However, in the walls obtained there is no steady formation of the lateral surface, which deteriorates with increasing transfer speed. It was deposited 10 layers walls with a total height of 8 mm, with a width of 3.3 mm for transfer speed 40 mm s\(^{-1}\), and 5.4 mm – for 10 mm s\(^{-1}\). For laser method was deposited 10 layers walls with height and width, respectively: 40 mm s\(^{-1}\) – 5.5 mm, 4.3 mm; 20 mm s\(^{-1}\) – 6.3 mm, 4.8 mm; 10 mm s\(^{-1}\) – 6.9 mm, 5.2 mm. It should be noted for this method that, when the number of layers increases, the size of the liquid bath decreases (loss of the proportion of molten metal from the substrate), and the melting of the wire becomes unstable. This caused the wire feed was reduced to 3 m min\(^{-1}\) at a speed of 20 mm s\(^{-1}\) (there is an increase of the liquid bath to the previous size, due to a greater melting of the previous layers).

The cross sections were made from the obtained samples (figure 6) to study the structure. It should be noted that the structure for all samples is similar to the cast structure, since in the grains there are tree-like crystals, the so-called dendrites. The formation of dendrites is related with nonequilibrium conditions of crystallization. As is known, the faster the liquid metal cools than the thinner the axis of the dendrites and the distance between them is smaller. This is due to the fact that with a large temperature gradient, the number of trunks and dendrite axes increases. In case of the laser method the geometry of the formation of the walls is better.

It can be seen from figure 6 that in all the samples a finely dispersed structure is observed at the base zone, the grains have a globular shape. As the wall grows, the grain grows too, acquiring an elongated shape. At laser deposition the grain have large area and located in few layers. At arc deposition method, each layer has its own crystallization centers.
Figure 6. The microstructure of different zone of deposited walls by arc (a,b) and laser (c,d,e) methods: Vt.s. = 10 mm s⁻¹ (a,c), Vt.s. = 20 mm s⁻¹ (d), Vt.s. = 40 mm s⁻¹ (b,e).

Figure 6a shown three main zone of grain formation (probably due to an increase in the intensity of mixing of the surfacing metal with the base metal of substrate). The zone near the substrate is characterized by small equiaxed grains (bottom), in the second layer, the grains become larger and stretch (middle), in 3-4 layer was obtained the formation mainly columnar elongated grains (top). When the transfer speed is increased to 40 mm s⁻¹ (6b), the grains are stretched considerably toward the heat removal side, and also their width is reduced. The average width, height, and height-to-width ratio are shown in table 4.

Figure 6c shown, that at the lowest used speed of 10 mm s⁻¹, the grain formation over the entire wall height is more uniform. The grains in structure are stretched considerably toward the heat removal side. In the structure, columnar grains are co-directional with the direction of heat removal. With increase of transfer speed was obtained two main zone of grain formation (like at arc method, due to an increase in the intensity of mixing of the surfacing metal with the base metal). The zone near the substrate is characterized by fine equiaxed grains (the mixing area), from the second layer, the formation is
predominantly columnar elongated grains. When the transfer speed is increased to 40 mm s\(^{-1}\), the grains are stretched considerably toward the heat removal side, and also their width is reduced (6e).

### Table 4. The average values of width, height and width-to-height ratio of grain.

| regime № | Grain width (μm) | Grain height (μm) | Height-to-width ratio | Transfer speed (mm s\(^{-1}\)) | Wire feed rate (m min\(^{-1}\)) |
|----------|------------------|-------------------|----------------------|---------------------------------|-------------------------------|
| arc      |                  |                   |                      |                                 |                               |
| 7        | 147,5            | 584,1             | 3,96                 | 10                              | 4,5                           |
| 12       | 129,5            | 924,5             | 7,13                 | 40                              | 4,5                           |
| laser    |                  |                   |                      |                                 |                               |
| 18       | 277,8            | 2123,5            | 7,64                 | 10                              | 2                             |
| 14       | 173              | 923,1             | 5,34                 | 20                              | 3                             |
| 19       | 152              | 1801,1            | 11,85                | 40                              | 5                             |

The best formation of the wall was obtained at reduced speed – 10 mm s\(^{-1}\). At a speed of 40 mm s\(^{-1}\) in the arc method, non-fusion was detected in the cross section. For the laser method also was detected an inadmissible, partial absence of complete melting of the wire at the wall growing, which was accumulated in the form uneven melting on the lateral surface. A comparison of the laser and arc methods is done for regimes № 7 and № 18.

For clarity, was constructed a graph of the grain size at the process of wall growing (figure 7). The number of grains by which the size was determined varied from 20 to 50, depending on the viewed area.

![The dependence of grain size change with wall growth](image)

**Figure 7.** The graph of the grain size at the process of wall deposition.

It can be seen from the graph that as the wall grows, the size of grain increases, especially in length. At laser method the grain size in length is several times larger than the grain size at arc method. Microhardness in the directions of wall growth and width was also measured for the samples. Schemes of measurements and graphs of microhardness distributions are presented in the figure 8 (a,b).
Figure 8. The distribution of microhardness in width (a) and height (b) of wall.

Figure 8a shows that the microhardness in the layer is higher than in the overlapping zone. And also small jumps of values of HV on width are visible. This is due to the impact of the measurement in different structural components. Minimal discrepancies in the microhardness in the layer and in the overlap zone are observed according to the regime №18. As the height of wall increase the microhardness decrease (figure 8b), there are also small jumps in the values of hardness in the layer and overlap zone, this is particularly pronounced in the laser method.

4. Conclusions
It was shown that both methods (laser and arc) of deposition give satisfactory results for growing the layer-by-layer walls from copper-nickel wire. Herewith, the most stable process was obtained at the speed of 10 mm s⁻¹, and, as a result, the best formation of layers, for both methods.

It was shown in metallographic studies the similarity of the structures of deposited samples by different methods. Minimal discrepancies in microhardness in the layer and in the overlap zone are observed during laser deposition. It was also found that as the wall grows, the hardness decreases, jumps in the values of hardness in the layer and in the overlap zone are observed.

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