Studying the layer structure formation in laser additive manufacturing with AlMg6 alloy wire

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Abstract. When processing aluminum alloys with repeated laser radiation, which is typical for both multi-pass welding and additive manufacturing, volatile chemical components are being burnt. Due to the processing zone overheating if there are residual stresses, the probability of there being structural defects and deformations and, consequently, distortion of the final shape of the sample increases. Studies of the wall’s structure forming process during laser additive manufacturing with AlMg6 alloy wire, fulfilled based on experiments and computational methods, allowed us to obtain the necessary data for optimizing the process and determining the laser treatment modes. The simulation of the thermocyclic effect of laser radiation on the wall and the selection of mode parameters for the optimal structure of the material and the shape of the bead were performed. The results for the chemical composition of the final material, the number of defects and mechanical properties were quite satisfactory.

1. Introduction

Research and development of additive technologies (AT) is a promising field for the production of metal parts with complex shapes. Their production using traditional methods is difficult and time-consuming [1-5]. The main research in the field of AT is aimed at studying the peculiarities of physical processes and methods of material application, using both powder materials and wires. In this case, a laser beam, an electron beam, an electric arc, as well as a combination of a laser beam and an electric arc can be an energy source [6-10]. Despite serious progress in the development of deposition technologies that use powder materials, the speed of parts manufacturing usually does not exceed 25 g/min [11].

The continuous process of deposition can take anywhere from a few days to several weeks when depositing of large-size details for ship industry and aircraft building. It can be much more effective to use wire as a filler material, especially in the manufacture of large products [12, 13]. In both cases, the deposition process is associated with intense material heating, so it is necessary to learn how to control this process to be able to control the formation of the wall. Uncontrolled heating can lead to overheating of the product. It will create conditions for structural defects and geometric distortion. Due to this, using a laser as an energy source looks more preferable in comparison to an electric arc, as the arc source has a larger heating area and thermal inertia, which means a longer response time to
control signals [14]. The use of a laser as an energy source leads to the formation of a unique thermal regime, which is characterized by high cooling rates and low melt pool volumes. The problem of the importance of selecting mode parameters, for example, for aluminum alloys is considered in [15-19], which demonstrates how significantly heat input can affect the shaping, the final structure and the existence of defects at the deposition of walls of an AlMg6 wire.

2. Simulation

One of the important advantages of additive manufacturing over traditional technologies is the possibility of influencing the geometric parameters and structure of the deposited layer by controlling the conditions of melting and crystallization of the melt pool with its subsequent cooling. The model of the heat transfer process during wire feed laser deposition [20-21] is used to calculate the temperature field obtained by solving the non-stationary heat equation with the Green's function method.

The following equation is used as the base (1):

$$\Delta T(x,y,z,t)=\frac{2q}{c\rho(4\pi a)^{3/2}}\exp\left(-\frac{v x^2}{2a}\right)\exp\left(-\frac{v^2}{4a}\left(t-t'\right)\right) \left(\frac{R(x,y,z)^2}{4a(t-t')}\right) dt'$$

where $q$ – the heat of an instantaneous heat source; $R$ – distance from the heat source to the point of the body under consideration; $v$ – heat source speed; $a$ – thermal diffusivity, equal to $a=\lambda/(c\rho)$; $\lambda$ – thermal conductivity; $c$ – specific heat capacity; $\rho$ – density; $b=2\alpha/(cpw)$ – coefficient of heat exchange; $\alpha$ – heat transfer coefficient; $w$ – wall width; $t$ – point in time; $t1$ – heat source start time; $t2$ – the time when the heat source ends its action, and $t > t2 \geq t1 \geq 0$.

Despite the fact that the heat transfer model was developed for processes where an electron beam acts as a heat source, it can also be used for a laser beam, because both of them can be represented as surface elliptical heat sources.

A simulation of the deposition process was performed for various values of laser power in the range of 4500 – 6500 W. Other parameters of the mode were as follows [22]: the angle of the laser beam relative to the vertical was 10°; the diameter of the laser spot on the sample surface was 5 mm; the cladding speed was 20 mm/s, the wire feed rate was 50 mm/s, the pause time between passes was 18 s.

The simulated sample is a single wall with a length of 80 and 160 mm and a height of 100 layers. It was decided to consider one point in the middle of the deposited wall and one point near its edge for analyzing the temperature state of simulated samples and calculating thermal cycles. During a real process the middle wall region has the greatest stability and the influence of edge effects on the point is minimal. A point in the edge region is characterized by a reduced heat sink. The arrangement of points under consideration is shown in Figure 1.
The simulation helped obtain the temperature distribution of the wall surface heating immediately before each pass, depending on the number of deposited layers (Figure 2).

The temperature difference of points 1 and 2 just before each pass was calculated to estimate the degree of heat accumulation at the end of the wall. Figure 3 presents the simulation results of the deposition process with constant power throughout all layers.

**Table 1. Change in laser radiation power depending on the number of passages**

| Passage | Power, W |
|---------|----------|
| 1-2     | 6500     |
| 3-10    | 5800     |
| 11-34   | 5200     |
| 35-66   | 4800     |
| 67-100  | 4500     |

In order to reduce the temperature difference at the selected points, a simulation was performed for the case of reducing the laser power as the wall height increases. The parameters of the mode with a change in the radiation power depending on the height of the wall (by layer) are shown in Table 1.

Based on the calculations, it can be concluded that when using a constant laser power during the deposition of the first layers, both the wall temperature as a whole and the temperature difference between points 1 and 2 increase. After about 30 layers, the temperature difference of points 1 and 2 almost stops growing and takes a constant value, but the overall temperature of the wall increases. However, a decrease in power with an increased number of layers leads to several effects. Firstly, the overall temperature of the wall decreases. Secondly, the temperature difference between points 1 and 2 decreases. This means that the heat at the edge of the wall accumulates to a much lower degree than in constant mode. Thirdly, even with an increase in the number of layers and with a decrease in power, the wall temperature does not increase. It can be seen, for example, in Figure 2 (dashed lines), when depositing between 65 and 80 layers.

### 3. Experimental

Thermocouple adjustment method was used to calibrate the thermal imaging camera. The scheme is shown in Figure 4.
Figure 4. Calibration diagram of the thermographic instrument, where P1 and P2 are the melting points of thermocouples.

Two thermocouples are soldered to the deposited wall at a distance of about 10 mm located at points P1 and P2, and the thermal imaging camera is installed at a certain distance from the sample. The choice of the number of thermocouples is explained by the need to fix the readings of two temperature ranges (150-950 C for the upper and 0-250 C for the lower thermocouple) for a more accurate calibration result. The upper layer is then poured onto the wall and the temperatures are measured. With the help of the coefficient of radiation adjustable on the thermographic instrument, the selection method achieves the result where the readings from the thermographic instrument and the thermocouple coincide with an error of less than 8%.

The LS-15 ytterbium fiber laser is used as a laser source with a maximum output power of 15 kW. The radiation was transported through a fiber optic cable to Precitec's YW50 ZK optical head with a focal length of 400 mm and a focal spot of 0.4 mm. The PDGO 601 wire feeder with a welding torch was used to move the wire to the working area of the process. 16 mm thick D16T aluminum plates and 1.2 mm AlMg6 wire were used in experiments, the chemical composition is shown in Table 2. The flow diagram of the process is shown in Figure 5.

Table 2. Chemical composition of wire and substrate

| Variables | Al   | Mg   | Mn   | Cu   | Zr   | Ti   |
|-----------|------|------|------|------|------|------|
| AlMg6 wire| 92.93| 6.3  | 0.65 | 0.06 | 0.1  | 0.03 |
| D16T      | 90.9-94.7 | 1.2-1.8 | 0.3-0.9 | 3.8-4.9 | <0.25 | <0.15 |

Figure 5. Scheme of the process, where 1 - Laser beam; 2 - wire feed; 3 - infrared camera (positioned perpendicular to the wall); 4 - Metal substrate; \( V_c \) - the direction of deposition; \( h \) - distance from the working point to the surface of the deposition.

Linear walls were deposited on the plate from the wire by successive superimposing of layers by laser in one direction and with variable direction. Argon was used as a shielding gas. The deposition test regimes selected from the simulation results are shown in Table 3.
Table 3. Deposition test regimes

| Variables                  | Regime №1 | Regime №2 | Regime №3 |
|----------------------------|-----------|-----------|-----------|
| Wire feed angle, (º)       | 35        | 35        | 35        |
| Laser head angle, (º)      | 10        | 10        | 10        |
| Laser power, kW            | 5.5       | 5.5       | 6.5-4.5   |
| Deposition rate, mm/s      | 20        | 20        | 20        |
| Wire feed speed, mm/s      | 50        | 50        | 50        |
| The diameter of the laser spot, mm | 5        | 5        | 5         |
| Pause between layers, s    | 10        | 22        | 18        |
| Wall length, mm            | 160       | 160       | 80        |

The quality of the walls was assessed visually and based on a metallographic analysis of the cross-section. Thermal imager Testo-890 with a sensitivity of 0.04 ºC and a temperature range from -30 to 1200 ºC was used to register temperature fields and their changes (Figure 6).

![Figure 6. Results of measuring the temperature field for sample №3: 1) 4 seconds from the start of the process; 2) 9 seconds from the start of the process; 3) 14 seconds from the start of the process; 4) 18 seconds from the start of the process.](image1)

Figure 7 shows the wall obtained in regime №1 with constant laser power. The onset of instability is observed at wall heights of 15 mm. The height of the resulting wall is 20-23 mm, width 4-5 mm.

![Figure 7. The sample obtained in test regime №1.](image2)

Figure 8 shows sample number 3. Overall dimensions of the wall: height 63 mm, width 4-5 mm. The total number of passes during laser wire deposition - 94. Steady formation was observed throughout the height, despite a slight widening of the wall at the edges. Also, the formation of cracks was observed in this zone.

![Figure 8.](image3)
4. Results and discussion

4.1. Comparison of simulation and experimental results

Based on the results of the experiment, it was possible to obtain thermal cycles using a thermal imager for points located on the surface of the sample. Furthermore, the conditions for crystallization of the melt pool and cooling of the wall were obtained by calculation.

Figure 9 shows a comparison of measuring and calculating temperature cycles at points 3 and 4 of sample №2, with Hp=12 mm (see Figure 1). The calculated temperature cycles have some deviations in places of temperature peaks when the x-coordinate of the point in question coincides with the axis of the laser beam.

At the same time, in areas of cooling or lowering the temperature, there is a fairly good coincidence of curves. This is primarily due to the fact that the analytical solution itself has an error in areas located directly near the action of the heat source. In this mode, the calculated and experimental cycles coincide satisfactorily.

The most stable formation was obtained on the sample with a decrease in power as the layers increased, on the sample with minimal edge overheating, which coincides with the results of the preliminary simulation. When using a constant power mode, there is a more pronounced overheating of the edge of the wall, which leads to loss of stability of the process.

At the edge of the wall, there is an increased heating temperature. Due to the accumulated at the edge of the wall heat, the width of the melt pool increases and, as a result, the layer height decreases locally. When the wall is flushed, the distance h increases, the formed drop at the end of the filler wire loses contact with the melt bath, and its separation from the wire occurs with a delay. Thus, the wall does not receive the necessary amount of building material, which leads to the formation of irregularities on the edges of the wall, up to complete loss of shape. Thus, a change in the transfer mode of the metal is one of the factors that affects the formation of swaths and slumps on the edge.

Also, it should be noted that there are cracks at the end of the wall. This is due to the accumulation of heat in this place, as can be seen from Figure 5. Consequently, it is necessary to make changes in the calculation of temperature cycles, in order to reduce overheating at the end of the wall.
4.2. Macrostructure and hardness

The transverse section of the central part of the sample was cut out of the wall, which is shown in Figure 10. Chemical etching in 10% aqueous solution of hydrofluoric acid [11 ml 48% HF + 100 ml H2O] was used for 30-60 seconds to reveal the structure.

![Figure 10. Macrostructure of the sample obtained in test regime №3. Unit hardness - HV](image)

The layered structure is observed in the sample. There are expressed disperse inclusions in the whole volume of the molten material (Figure 9). Optical microscopy has shown that the structure is a matrix based on a solid aluminum solution with evenly distributed disperse inclusions containing Al, Mg, Cu, Mn. Microhardness was measured inside and between the layers, the average microhardness is 75 HV. The average height of layers is 550±100 µm.

There is some incomplete fusion at the edges in the upper zone of the wall that was created at a power of 4.5 kW. Perhaps it is due to the laser radiation’s lack of power density for remelting the filler material at the edges of the spot. There are pores that do not exceed 50 µm in diameter.

4.3. Chemical composition

When depositing aluminium alloys at high temperatures, the alloying elements, such as magnesium, burn out. The amount of magnesium in the filler wire is increased to maintain the required concentration in the deposited wall.

In the wall section, where the power of laser radiation was 4300 W, losses of magnesium were recorded up to 17% (Figure 11).

![Figure 11. Measurement points (a): zone №1 (11% losses Mg), zone №2 (17% losses Mg), zone №3 (14% losses Mg); and chemical composition determination area (b) (zone №3).](image)
5. Conclusion
Thus, we can conclude:

- A decrease in power with an increase in the number of layers leads to a decrease in the overall temperature of the wall; to a decrease in the accumulation of heat at the edges of the wall; to an earlier cessation of the increase in wall temperature.
- The most stable formation of the wall is obtained when the input power of laser radiation decreases as the number of layers increases.
- The stability of the wall formation is affected by the value of parameter h. As the working distance increases the mass transfer of metal becomes drip, moreover the droplets hit the melt bath with a delay. The necessary amount of building material does not enter the wall, which results in irregularities at the edges of the wall, up to complete loss of shape.
- Cracks may occur due to excess power and when the laser radiation is in the overheating zone for a long time.
- The obtained hardness values for the sample with reduced wall height power were satisfactory and averaged 75 HV, which corresponds to the normal hardness of the alloy in question.
- Analysis of chemical composition in all sections of the wall, regardless of the power range, showed a burnout of Mg of no more than 17%.

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