Features of structure formation and properties at laser and arc surfacing from steel wire

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Abstract. The publication is devoted to research of deposition cylinders with the help of arc and laser surfacing using steel wire Power Pipe 60M. The influence of various regimes on the formation of weld beads and their geometry is studied. The effect of the regime on the formation of the structure of the obtained samples is analyzed, and a comparative analysis is carried out between arc and laser surfacing of grown cylinders. High-quality samples with good structure and properties were obtained.

1. Introduction
Nowadays the intensive development of additive technologies makes it possible to significantly improve the methods of manufacturing and processing products [1]. One of the promising areas for the development of modern industry are additive ("adding") technologies, including the process of direct laser growing, which is based on the principle of controlled product formation due to the local input of material into the desired place [2]. At the same time, the boundaries of technological and design capabilities are widening, as full automation and "digitalization" of the process takes place. Such an approach expands wide opportunities in shipbuilding, machine building, rocket and space industry, medicine [3]. This technology allows to reduce the technological stages of production. So it allows to reduce time for production and the final cost of goods.

The speed of growing from the wire allows to increase the productivity and the utilization factor of the material (it is about 70-90%).

2. Experimental procedure
2.1. Experimental equipment
At the process of arc surfacing Taurus 551 Synergic S FDW with a maximum welding current of 550A was used as a power source for the welding arc. Laser surfacing was performed using the «Rechflot» technology complex based on a powerful fiber ytterbium laser LS-16 with a maximum output power of 16 kW. At laser surfacing wire feeder mechanism with PDGO - 601 was used.

At the experiments we used steel wire Power Pipe 60M (with diameter 1.2 mm), as a substrate steel plates were used (thick: 7, 8 and 10 mm) of the PSE 36 mark.

During the arc-surfacing process, the burner was located perpendicular to the support plate.

2.2. Arc-surfacing of single weld beads
At the arc surfing technology the process speed range from 7 to 20 mm/s is considered. Surfacing of weld bed No. 11 and No. 10 is performed in a pulsed mode of wire feeding, other weld bead are performed with continuous mode.

With the deposition rate \( V = 15 \text{ mm/s} \) the weld bed No.11 made in the pulsed mode of wire feeding has a lower linear energy than the continuous feed No. 12 in the table 1, and accordingly it has the minimum penetration depth.
Table 1. The mode parameters for single weld bed.

| No. | I, (A) | U, (V) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-----|--------|--------|----------------|--------|----------|---------|
|     |        |        |                |        |          |         |
| 11  | 74     | 16     | 1,5            | 0,70   | 79       | +       |
| 12  | 143    | 17,7   | 1,5            | 0,97   | 169      | +       |

Surfacing speed 20 (mm/s)

| No. | I, (A) | U, (V) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-----|--------|--------|----------------|--------|----------|---------|
| 1   | 100    | 16,5   | 2              | 0,58   | 83       | -       |
| 2   | 147    | 17,1   | 3              | 0,78   | 126      | +       |
| 3   | 148    | 17,2   | 3              | 0,62   | 127      | +       |
| 10  | 74     | 16     | 1,5            | 0,59   | 59       | +       |
| 13  | 144    | 17,5   | 1,5            | 0,95   | 126      | +       |
| 14  | 147    | 17,4   | 1,5            | 0,85   | 128      | +       |
| 15  | 179    | 13,5   | 1,5            | 0,79   | 121      | +/-     |

At the deposition rate \( V = 20 \text{ mm/s} \) we can say that an increase in wire feed speed from 2 to 3 m/min has gained to satisfactory appearance of the weld beds. However, the depth of penetration of these weld beds became higher. The weld beds No.13 and No.14 at the continuous mode turned out to be more steady, but they have the maximum depth of penetration.

Weld bed No.10 made in a pulsed mode of wire feeding has a satisfactory appearance, and also it has a minimum penetration depth and a minimum value of rate of energy input.

The specific energy of metal melting at \( V = 20 \text{ mm/s} \) is given in table 2.

Table 2. Specific energy of metal melting.

| No. | Q<sub>s</sub>, (J/g) |
|-----|---------------------|
| 1   | 6111                |
| 2   | 7393                |
| 3   | 8485                |
| 10  | 5148                |
| 13  | 7200                |
| 14  | 5813                |
| 15  | 4833                |

Weld beds of satisfactory quality were obtained at a deposition rate 20 mm/s. The wire feed speed 1.5 m/min stably ensures a good formation of the weld bed. So for further experiments we choose this speed.

2.2.1. Walls growth by the method of arc-surfacing

Table 3. Selection of modes for deposition walls by the method of arc-surfacing.

| No. | I, (A) | U, (V) | V wire, (m/min) | Q, (J/mm) | grading |
|-----|--------|--------|----------------|-----------|---------|
|     |        |        |                |           |         |
|     |        |        |                |           |         |
| 1   | 74     | 16     | 1,5            | 59        | -       |

Surfacing speed 10 (mm/s)
The wall No.1 was grown with a pulsed mode of feeding the wire. The result of multilayer surfacing process under this regime was not satisfactory. Formation of large waves and melting of the weld bed were observed. The deposition rate was reduced to 10 mm/s. Visual inspection showed the presence of droplets on the surface. For further experiments we select the process speed 7 mm/s.

With the deposition rate $V = 7$ mm/s three walls were grown by the method of arc surfacing at the pulsed mode of wire feeding figure 1.

Wall a) consists of 15 passes. During the experiment a temporary pause between passages was not recorded.

Wall b) consists of 22 passes. The pause between passages was fixed. The pause between passages 1-12 was 2 minutes, between passes 12-22 it was 1 minute.

Wall c) consists of 10 passes. Then the pause between passes was reduced to 30 seconds.

| Surfacing speed 7 (mm/s) | 1-11 | 12-13 |
|-------------------------|------|-------|
|                         | 74   | 74    |
|                         | 16   | 16    |
|                         | 1,5  | 1,5   |
|                         | 118  | 169   |
|                        +/- |      | +/-  |

Walls of satisfactory quality were obtained at a process speed of 7 mm/s. Growing walls at high speed is accompanied by the formation of large waves.

Reducing of the pause between the passes led to a growing wall by 30%.

In conclusion, we can say that a satisfactory formation was obtained with a rate energy input 169 J/mm in the table 3.

2.3. Laser-surfacing of single weld beds

The scheme of the laser surfacing process is shown in figure 2. The angle of the burner 45° from the vertical, the laser head - 15°.
Figure 2. Left: Illustration of the laser-wire interaction. The molten metal solidifies into a bead by relative motion of the welding tool and the substrate. Right: Top- and side view images of the real process [4]

Table 4. Selection of a mode for laser surfacing of single weld beds.

| No. | P, (W) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-----|--------|----------------|---------|-----------|---------|
|     |        |                |         |           |         |
|     |        |                |         |           |         |
|     |        |                |         |           |         |

Surfacing speed 20 (mm/s)

| No. | P, (W) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-----|--------|----------------|---------|-----------|---------|
| 1.1 | 12000  | 4              | 1.96    | 600       | -       |

Surfacing speed 10 (mm/s)

| No. | P, (W) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-----|--------|----------------|---------|-----------|---------|
| 1   | 6000   | 2.1            | 1.65    | 600       | +       |
| 2   | 4000   | 2.1            | 1.01    | 400       | +       |
| 3(2)| 4000   | 2.1            | 0.92    | 400       | +       |
| 4   | 6000 (15/5) | 2.1    | 1.12    | 600       | +       |
| 5   | 6000 (10/5) | 2.1    | 0.85    | 600       | +       |

A final weld beds have a satisfactory appearance. Weld beds No. 2 and No. 3 in the table 4 have a lower running energy. The process speed 10 mm/s ensures satisfactory formation of the weld beds, so we will use it for further experiments.

2.3.1. Walls growth by the method of laser-surfacing

To estimate the power limits we make surfacing at the range of 4-6 kW is given in table 5.

The wire feed is based on the possibility of its melting at a power level from 4 to 6 kW.

Table 5. Selection of modes for deposition the walls by laser surfacing.

| No. | No. pass | P, (W) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-----|----------|--------|----------------|---------|-----------|---------|
|     |          |        |                |         |           |         |
|     |          |        |                |         |           |         |
|     |          |        |                |         |           |         |

Surfacing speed 10 (mm/s)

| No. | No. pass | P, (W) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-----|----------|--------|----------------|---------|-----------|---------|
| 6   | 6.1-2    | 6000 (10/5) | 1.86 | 0.85    | 600       | -       |
| 7(2)| 7.1-2    | 4000   | 2.1            | 0.84    | 400       | -       |
| 8   | 8.1-2    | 5000   | 2.1            | 1.22    | 500       | +       |
Walls No.6 and No.7 consist of two passes and have unsatisfactory appearance. We took a decision to choose the average value of the emission power from the power range (5 and 4.5 kW). It resulted in a satisfactory result: wall No.8 differs in the uniform formation and absence of defects.

Satisfactory results were obtained with a laser emission power of 4.5-5 kW. In future we will use exactly this power.

In conclusion, we can say that a satisfactory formation was obtained with rate of energy input of 450-500 J/mm.

3. Experimental results

3.1. Cylinder growth by arc-surfacing method

A cylindrical specimen was grown by the arc-surfacing method of the pulsed mode of wire feeding with the deposition rate $V = 7$ mm/s. The parameters of the regime are shown in the table 6. The number of passes was 50. The diameter of the cylinder was 90 mm. Cultivation was carried out on 5 repeats; pause between repeats is 2 minutes.

### Table 6. Cylinder cultivation mode arc-surfacing method.

| I, (A) | U, (W) | V wire, (m/min) | H, (mm) | Q, (J/mm) | grading |
|-------|--------|----------------|--------|----------|---------|
| 74    | 16     | 1.5            | 0.63   | 169      | +       |
The depth of penetration of the substrate at the first pass is 0.63 mm. The average thickness of subsequent layers is 0.8 mm. The average thickness of the grown wall is 2.9 mm.

3.2. Cylinder growth by laser surfacing

At the deposition rate $V = 10$ mm/s, a cylindrical specimen was grown by laser surfacing. The parameters of the mode are shown in Table 7. The diameter of the cylinder was 60 mm. Pause between passes is 5 minutes.

### Table 7. Cylinder cultivation mode laser-surfacing method.

| No. pass | $P$, (W) | $V_{wire}$, (m/min) | $H$, (mm) | $Q$, (J/mm) | grading |
|----------|----------|---------------------|----------|-------------|---------|
| 1-2      | 5000     | 2,1                 |          | 500         | +       |
| 3-4      | 4500     | 2,1                 |          | 450         |         |
| 5-7      | 5000     | 2,1                 |          | 500         |         |
| 8-11     | 5000     | 1,86                | 1,62     | 500         | +       |
| 12       | 5000     | 2,1 error           |          | 500         |         |
| 13-16    | 5000     | 1,86                |          | 500         |         |
| 17-43    | 4500     | 1,86                |          | 450         |         |

Overheating of the metal was observed at first two passages. We took a decision to reduce the emission power from 5 to 4.5 kW. However, at this mode wire was not melted, so we returned to a power of 5 kW and reduced the wire feed speed, which led to a positive result. Melting of the last layer is observed.

The result obtained by LM growth is satisfactory. The process was carried out with speed 10 mm/s. Variation range of rate of energy input is 450-500 J/mm.

The depth of penetration of the substrate at the first pass is 1.62 mm. The average thickness of subsequent layers is 0.4 mm.

The average thickness of the grown wall is 5 mm.

3.3. Compare of laser-surfacing and arc-surfacing

Let's compare the results of growing cylindrical samples with two technologies. For the convenience of analysis we introduce the range of parameters in Table 8. The $Q$ value is calculated for 1 pass.

### Table 8. Comparison of modes of laser-surfacing and arc-surfacing.

| $V$, (mm/s) | $V_{wire}$, (m/min) | $H$, (mm) | $a$, (mm) | $S$, (mm²) | $Q$, (J/mm) | $Q_s$, (J/g) |
|-------------|---------------------|----------|-----------|------------|-------------|-------------|
| laser-surfacing |                    |          |           |            |             |             |
| 10          | 1,86-2,1            | 1,62     | 5         | 109,13     | 450-500     | 22730       |
| arc-surfacing | 7 | 1,5 | 0,63 | 2,9 | 135,96 | 169 | 7975 |

Analyzing table 8, we realize that the wire feeding speeds of the growing processes by the DN and LN methods differ with 25%. The depth of penetration of the substrate at the first pass is 2.5 times lower at DN.

Also, the process of growing by the DN method is characterized by a low rate of energy input, which is 3 times less than for LN.

In addition, the melting of a unit of mass of material because of laser growth consumes almost 3 times more energy.

3.4. Metallographic research
In the welded metal by means of a laser, the structure consists of fine-needle ferrite, the fraction of which is not large because of the low content of Mn, in the lower part of the melt bath, elongated dendrites, and in the upper - disoriented grains. This structure was formed due to surfacing of subsequent layers, heat transfer from the 2nd layer to the 1st pattern figure 6 a.

In fused metal in the lower part of the widmanstatten ferrite and fine needle ferrite figure 6 b.

![Figure 6. a) laser bottom, b) arc bottom](image)

The structure of the surfacing in the middle of the grains is needle ferrite figure 7 a. In figure 7 b, the upper part shows the growth of dendrites, the structure of fine-needle ferrite.
**Figure 7.** Macrostructure of the samples at the top a) laser surfacing b) arc surfacing

**Figure 8.** Microstructure of the samples a) laser surfacing at the top, b) laser surfacing at the middle, c) laser surfacing at the bottom, d) arc surfacing at the height, e) arc surfacing at the middle, f) arc surfacing at the bottom
In figure 8 a) the intergrowth of the widmanstatten ferrite "decorates" the boundaries of the austenite elongated grain, d) the fine needle ferrite structure, the ferrite is observed along the boundaries, b) the ferrite structure, with an admixture of fine-needle ferrite, c) the ferrite structure, c) the needle ferrite structure with a small amount of ferrite, d) a needle-ferrite structure with a widmanstatten ferrite [5-8].

![Figure 9](image)

**Figure 9** - Measured microhardness along the build height for a samples fabricated by laser surfacing and arc surfacing.

The microhardness in the grown cylinder with a laser is proportionally higher than that of the arc, because of the greater energy input and the high cooling rate (figure 9).

**Conclusions**

Number of experiments were conducted during the work on growing the walls by the method of arc surfacing and laser surfacing. It is shown that in the case of arc surfacing at a process speed of 20mm/s, the result was unsatisfactory. To obtain walls of satisfactory quality, multilayer surfacing was performed at a reduced speed (7 mm / s). In the case of laser deposition, it is shown that at a speed of 10 mm/s and a radiation power of 6kW and 4kW, the resulting walls have an unsatisfactory appearance. A satisfactory result was obtained at a radiation power of 4.5 and 5 kW.

The process of growing a cylinder by laser surfacing is characterized by a running energy of 450-500 J / mm, and the arc surfacing method is 169 J / mm, which is an advantage of the technology.

In the structure of the obtained cylindrical samples along the grain boundaries, a widmanstatten ferrite is observed - the structure has two characteristic features: coarse-grained and a definite directionality of the plates. Such a structure is considered defective and in critical details is unacceptable. It must be eliminated by complete annealing or normalization. The widmanstatten pattern is a sign of steel overheating, which is also observed with laser and arc surfacing.

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