Distortion of AISI 1020 steel substrate in the process of laser cladding of E-300 powder material

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Keywords: laser powder cladding, distortion of the substrate, AISI 1020, powder E-300, depth of the mixing layer, thermocyclic tests.

Abstract. The results of experimental studies to determine the effect of power during laser powder cladding on temperature deformations of the substrate at a constant cladding rate and the mass flow rate of the powder are presented. Steel 1020 was used as the substrate material, from which samples of sizes 90x90 mm and a thickness of 8 mm were made. Laser powder cladding was performed by using a wear-resistant powder E-300 on a robotic complex with an ytterbium fiber laser and a coaxial powder feed. Single tracks were applied to the sample by laser powder cladding using various parameters of technological modes. The amount of deformation of the substrate was estimated taking into account the depth of the mixing layer. The cladding mode is selected, which provides minimal temperature deformations, with maximum process performance.

1. Introduction

Cladding of wear-resistant coatings is one of the most widely used methods for restoring the working surfaces of mating parts. This is justified by the possibility of applying a relatively small layer of cladding material with good wear-resistant, corrosion-resistant properties to a substrate made of inexpensive grades of steels. This technology significantly reduces the cost of manufacturing parts of critical components [1-3]. There are several technologies for applying wear-resistant cladding materials. One of the most common methods of performing repair and restoration work on cars is manual welding with electrodes. This method has a high labor intensity and a number of technological disadvantages [4]. The manual method of coating is gradually being replaced by the method of laser powder cladding, which has a number of advantages, including: increased process speed, less heat input into the substrate, which allows you to have less influence on the substrate, as well as achieve the required coating properties already on the first applied layer, as well as the possibility of reducing the allowance for mechanical processing of the surfaces of the deposited coating (layers) to 0.5 – 1.0 mm, reducing the number of layers from 5 to 3 compared to analogues required to obtain a coating material corresponding to the chemical composition of the powder material due to reduced mixing with the substrate material [5]. The only significant disadvantage of laser powder cladding is a small range of technological modes (radiation power, speed of movement of the laser head, powder consumption), which can be applied to a specific powder/substrate pair [6].
This work was carried out within the framework of the Federal Target Program on the topic "Development of technology for obtaining wear-and corrosion-resistant sealing surfaces of high hardness for nuclear power plants by laser powder cladding". The purpose of the work was to obtain a wear-resistant coating to reduce the cost and improve the performance of a wedge gate valve operating at a temperature of up to 350°C and an operating pressure of up to 20 MPa.

The following tasks were set to develop a technology for applying wear-resistant coatings by powder laser cladding:

1. To investigate the influence of the parameters of the laser powder cladding process on the geometry of the deposited roller (height, width, depth of the mixing layer of the deposited and base material).
2. The choice of the cladding mode: for the first layer of cladding, the minimum penetration of the substrate, for subsequent layers, the maximum productivity and the height of the cladding.
3. Coating of experimental products, according to the design documentation agreed with the Customer.
4. To conduct a full cycle of studies regulated by RD 2730.300.06-98, which showed that the cladded coatings meet the claimed requirements when using them as sealing surfaces for nuclear power plants.
5. To produce experimental products of an Industrial partner with wear-and corrosion-resistant coatings using the developed method.

This paper presents a part of the conducted studies concerning the effect of laser radiation power on temperature deformation when cladding E-300 powder on a substrate made of steel AISI1020.

The factor of distortion of the substrate largely determines the possibility of using the proposed technology, since internal stresses in the substrate can lead to premature breakdowns in the node and its failure.

Studies of gas-powder laser cladding were carried out for a single tracks, for which its form, height, width, and depth of penetration in the substrate were determined [7-9], however, the study of the influence of the penetration depth during laser powder cladding on the amount of distortion of the substrate is a poorly studied direction.

The scope of application of the results of gas-powder laser cladding of a multilayer coating is planned to be used in the production of sealing surfaces of wedge and return valves with a nominal diameter from 80 to 600 mm, used at temperatures up to 350°C and pressure up to 20 MPa.

This powder material can be successfully used in the creation of coated products, taking into account the annual production of pipe fittings in the manufacture of valves at a reduced cost [5, 10-13].

2. Experimental

To conduct experimental studies, a laser robotic cladding complex (LRC-C) was used, including: a 6-axis industrial robot, a single-column powder feeder designed for the metered supply of powder material to the cladding head; an experimental laser cladding head with a powder supply module from four sides, the use of this nozzle was considered by the author [14], where it was found that it provides the formation of a set continuous flow of powder material into the cladding zone. The radiation source was a 3 kW ytterbium fiber laser. To ensure safe operation, the experiments were carried out in a modular protective cabin with an active laser safety system [15-17].

As a cladding material, a metal powder E-300 was used for laser cladding with a particle size of 63-125 microns made according to TU 14-22-250-2013, deposited on the substrate of steel AISI1020. After heat treatment, the hardness of the cladding is 37-39 HRC. The largest mass fraction in the powder: Fe is about 66 %; alloying components: Cr-17.7 %. Ni-7.97 %. Si-5.55 %. Mn-1.93 %. and the other components (C, Co) are hundredths of a percent.

Laser cladding was performed using continuous laser radiation in protective and transporting pure argon gas (purity 99.998%), flowing at a speed of 6 l/min and 25 l/min, respectively.

Figure 1 shows a diagram of the deformation of the plate surface after cladding in the longitudinal and transverse directions as a result of the action of temperature loads.
To assess the deformation during laser cladding, an experiment was carried out on laboratory samples: the sample dimensions are 90x90 mm, the substrate thickness is 8 mm. Cladding was performed when the laser power $P_l$ changed from 2000 to 3000 W in increments of 200 W, and the scanning speed $V$ is 6 mm/s. The mass flow rate of the powder was constant is $q = 15$ g/min. The length of the clad track was 90 mm. Before cladding, the surface of the substrate was pre-cleaned and not heated.

Upon completion of the cladding, the sample was subjected to temperature deformation, as a result, points 1-8 (Figure 2) received a vertical movement from the surface of the support table.

Then, by metallographic analysis, the geometric dimensions (in particular, the depth of penetration) on the transverse sections of the obtained samples were studied. Based on the obtained values, the estimated mass of the deposited material was calculated, which was then compared with the actual one.

3. Results and discussion

Figure 3 shows the vertical movements of points 1, 7 and 4 at the beginning of the cladding. It is assumed that the $Y$-axis runs along the line 1-7-4 with the origin at point 1.
Figure 3. Vertical movement of points 1 (at the origin), 7 (at Y= 45 mm) and 4 (Y= 90 mm) at laser radiation powers: 1-3000 W, 2-2800 W, 3-2600 W, 4-2400 W, 5-2200 W, 6-2000 W

Figure 4 shows the vertical movements of points 3, 8 and 6 at the end of the cladding.

Figure 4. Vertical movement of points 3 (at the origin), 8 (at Y= 45 mm) and 6 (Y= 90 mm) at laser radiation powers: 1-3000 W, 2-2800 W, 3-2600 W, 4-2400 W, 5-2200 W, 6-2000 W

As follows from Figures 3 and 4, the vertical movements of the end points of the beam as a result of its temperature deformation increase with increasing laser radiation power. With the same mass flow rate of the powder $q$, this leads to a greater depth of penetration of the substrate $d$. This follows from the photos shown in Figure 5 of the cross-sections of the single tracks sections deposited on laboratory samples.
Figure 5. Cross sections of single tracks at the following laser radiation powers: a-2000 W, b-2200 W, c-2400 W, d-2600 W, e-2800 W, f-3000 W

To quantify the effect of the laser radiation power on the penetration depth and, accordingly, the deformation of the substrate (based on the results of vertical movements of the nodal points of the laboratory sample), the measurement results are shown in Table 1.

When cladding, a part of the powder falls into the laser radiation zone and melts, forming a track. Since at the mass flow rate of the powder $q$ g/min and the cladding speed $V$, mm/s, the mass of the metal in the track with a cross section $S$ after 1 second can be determined as $q_r = SVp$ ($p=7800...7900$ kg/m$^3$ – the density of the metal formed after melting the powder), the efficiency of the powder material $k$ is equal to:

$$k = \frac{SVp}{q}$$

This method of determining the performance turned out to be quite convenient, since the study of micro-grinds of the cross-sections of the sprayed rollers was always carried out, which made it possible to always check the cross-sectional area and, accordingly, the performance of the sprayed powder $q_r$. To verify the correctness of the $q_r$ definition, the following experiments were carried out. Six laboratory samples of steel 20 were selected as a substrate, the mass of which was determined before cladding. After cladding the roller, the mass of the sample with the deposited roller was again determined and the actual mass of the sprayed roller was determined by the mass difference before and after spraying. According to the known time of deposition of the roller and the calculated value of $q_r$, the calculated mass of the sprayed powder can be determined. The results of the experiment are shown in Table 2, from which it follows that the measurement error is permissible.

Table 1. Linear dimensions of the deposited track made of PM-08H17N8S6G powder on a substrate made of steel 1020, depending on the laser radiation power.
Laser radiation power, W  | Track height, mm | Track width, mm | Penetration depth, mm | Movement in points, mm |
|------------------------|-----------------|-----------------|-----------------------|------------------------|
|                         |                 |                 |                       | section 1-7-4 | section 3-8-6 |
|                         | № 1 | № 7 | № 4 | № 3 | № 8 | № 6 |
| 2000                    | 0,680 | 3,765 | 0,044 | 0,26 | 0,01 | 0,14 | 0,28 | 0,01 | 0,32 |
| 2200                    | 0,738 | 4,618 | 0,049 | 0,28 | 0,02 | 0,17 | 0,31 | 0,01 | 0,36 |
| 2400                    | 0,738 | 4,339 | 0,053 | 0,34 | 0,01 | 0,25 | 0,39 | 0,02 | 0,39 |
| 2600                    | 0,760 | 5,032 | 0,058 | 0,36 | 0,00 | 0,27 | 0,40 | 0,01 | 0,42 |
| 2800                    | 0,751 | 5,231 | 0,342 | 0,56 | 0,02 | 0,33 | 0,54 | 0,01 | 0,20 |
| 3000                    | 0,849 | 4,987 | 0,373 | 0,70 | 0,01 | 0,49 | 0,57 | 0,02 | 0,30 |

**Table 2.** Comparison of the results of determining the mass of the sprayed powder.

| Laser radiation power $P$, W | Cladding speed $V$, mm/s | Weight of the substrate before cladding, g | Weight of the substrate after cladding, g | Weight of the sprayed powder, g | The surface area of the coating is calculated, $mm^2$ | Weight of the sprayed powder is calculated, g | The difference between the dimensions, g | The difference between the dimensions, % |
|-----------------------------|--------------------------|------------------------------------------|------------------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| 2000                        | 6                        | 493,58                                   | 494,87                                   | 1,44                           | 2,041                           | 1,432997                       | 0,007003                        | 0,486319                        |
| 2200                        | 6                        | 499,06                                   | 500,71                                   | 1,68                           | 2,351                           | 1,650537                       | 0,029463                        | 1,753750                        |
| 2400                        | 6                        | 502,45                                   | 504,11                                   | 1,86                           | 2,604                           | 1,828175                       | 0,031825                        | 1,711022                        |
| 2600                        | 6                        | 503,62                                   | 505,29                                   | 2,07                           | 2,843                           | 1,996106                       | 0,073894                        | 3,569758                        |
| 2800                        | 6                        | 502,52                                   | 504,47                                   | 2,28                           | 3,114                           | 2,186241                       | 0,093759                        | 4,112237                        |
| 3000                        | 6                        | 504,29                                   | 506,25                                   | 2,13                           | 2,923                           | 2,051874                       | 0,078126                        | 3,667887                        |

Note that the value of the mass of the sprayed powder calculated in Table 2 for all measurements was lower than the value obtained from the mass difference of the sample before and after cladding the roller. This may be caused by an error in determining the cross-sectional area of the track, when the measurement was not carried out strictly perpendicular to the axis of the track. Despite this, the deviations between the two calculation methods are small, they are within the measurement error.

On the basis of the conducted research, experimental samples were made in the selected technological modes (Figure 6).
Since distortions increase internal stresses, and taking into account the specifics of the task, we needed to create a coating with the lowest internal stresses that can withstand cyclic loads in a given temperature range, high values of the penetration depth on the first layer of cladding were unacceptable.

These coatings were tested under cyclic thermal load. Thermal tests consisted of sequential heating of experimental samples in a furnace at a temperature of 320°C, their subsequent exposure at this temperature for 2 hours, followed by a sharp cooling in water at a temperature of 20°C. To confirm the thermal stability, the experimental sample had to withstand 15 such cycles. After the tests were completed, the deposited surface was subjected to capillary inspection for cracks. As can be seen from the figure 7, the selected technological mode meets such requirements.
Figure 7. A sample that has passed cyclic tests after capillary control

4. Conclusion

According to the results of the conducted studies, the following results were obtained:
- The following dependence is revealed – the depth of penetration during cladding increases with increasing laser radiation power, with the same mass flow rate of the powder, this leads to large temperature deformations of the substrate.
- The cladding mode is selected, which provides minimal temperature deformations, with maximum process performance. The following parameters are optimal: laser radiation power, $P = 2600$ W; scanning speed, $V = 6$ mm/s; the mass flow rate of the powder, $q = 15$ g/min.
- Experimental coated products were manufactured that passed the full cycle of studies regulated by RD 2730.300.06-98 (thermocyclic tests and capillary control of the obtained experimental samples were carried out, as a result, no defects were detected on the control group of samples).

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