Evaluation of influence of technological parameters on width of strengthened layer in plasma surface hardening of structural steels

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Abstract. The article presents the results of the studies of the influence of technological parameters of plasma hardening on the geometric dimensions of the hardening track using modern research methods. The visualization of the heating spot on the metal surface according to the methodology made it possible to further evaluate the role of anode and cathode spots on the formation of a common heating spot in the process of plasma hardening of metals. It was established that, depending on the effective thermal power of the plasma arc, there are several modes of combustion of the plasma arc. For example, at an arc current of 20 A, there are several characteristic anode spots on the surface in the form of regular circles, which, with an increase in the arc current, contract to the center of the common heating spot. It has been established that the speed and distance of hardening affects the width of the hardened zone during plasma surface hardening of metals. The region of existence of several regimes of plasma hardening in a common heating spot was revealed, for which both single and group anode spots are characteristic.

1. Introduction
Due to the unique qualities of a compressed arc and a plasma jet as a source of heating the treated zone, plasma technologies affirmed in the general arsenal of other methods of surface treatment of metals [1-3]. A plasma jet and a compressed arc provide not only a thermal, but also a powerful force effect on the zone processing [4, 5]. The successful combination of high power and energy concentration in a compressed arc with the possibility of using a wide range of welding and auxiliary equipment designed for arc methods of metal processing suggests the prospect of using plasma technologies for surface hardening of various parts of machines and tools. At the same time, it must be recognized that very few papers have been devoted to theoretical issues of plasma surface hardening [1-3]. Moreover, the arsenal of plasma surface hardening technologies is expanding due to the development of new methods [4]. This paper presents the results of a study of plasma surface hardening from the standpoint of assessing the behavior and nature of the combustion of a plasma arc in argon. It is known [5-12] that the arc is a kind of gas insert between the electrodes and, like any conductor, interacts with magnetic fields. In this case, the pillar of the plasma arc can be considered as
a flexible conductor, which, under the influence of a magnetic field, can move like any other conductor, deform and lengthen [5-8]. This leads to the deflection of the arc in the opposite direction to the greater tension. From a technological point of view, the possibility of controlling a plasma arc opens up great prospects for processing extended surfaces [3,4].

2. Experimental methodology and materials

All work was carried out in the laboratory of hardening and surfacing of materials at Irkutsk National Research State Technical University. This laboratory is equipped with a plasma hardening and surfacing installation. The design of this installation includes several basic elements that perform their function. In the installation, it is possible to highlight such key nodes as:

- the working body (as a working body used the power source of the plasma torch, which produces hardening and surfacing);
- high-speed camera (allows fixing and monitor all processes occurring in the process of arc burning);
- a camera (allows fixing in color the process of formation of cathode and anode spots, as well as observing the size of the hardening zone, the formation of the weld pool and the nature of arc burning) [3,4];
- an oscilloscope (allows measuring and plotting the voltage and strength of the welding current throughout the process),
- as a movement, a special mobile installation was used, providing movement of the product itself relative to the welding head;
- to increase the width of the hardening zone, a magnetic expansion scheme is applied (based on an alternating current inductor).

3. Research results

During the study, plasma hardening of steel 45 was performed. In order to determine the width of the hardening zone, the surface was first treated mechanically (using sandpaper), then the steel was etched with a 5 % solution of nitric acid in alcohol. The figures show photographs of hardened surfaces. Figure 1 shows photographs of a surface hardened at a speed of 11 mm / s with an arc gap of 3 mm after machining and chemical etching. Table 1 shows the width of the hardened zone of the plate.

![Figure 1. Hardening speed 11 mm / s, arc length 3 mm, surface after etching.](image-url)
Table 1. Width of the zone of the hardened plate, mm.

| Hardening area | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|----------------|-----|-----|-----|-----|-----|-----|-----|
|                | 20A | 30A | 50A | 70A | 90A | 110A| 120A|
| Start          | 1.7 | 2.0 | 3.4 | 3.9 | 4.2 | 5.0 | 5.0 |
| Average        | 1.0 | 1.5 | 1.8 | 2.7 | 3.8 | 4.6 | 4.8 |
| Final          | 1.0 | 2.0 | 2.7 | 3.0 | 3.0 | 4.4 | 4.5 |

Figure 2 shows photographs of the surface hardened at a speed of 11 mm / s with an arc gap of 8 mm after hardening, as well as after mechanical processing and chemical etching. Table 2 shows the width of the hardened zone of the hardened plate.

![Figure 2](image-url)

Table 2. Width of the zone of the hardened plate, mm.

| Hardening area | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|----------------|-----|-----|-----|-----|-----|-----|-----|
|                | 20A | 30A | 50A | 70A | 90A | 110A| 120A|
| Start          | 1.4 | 1.9 | 2   | 2.5 | 4   | 4.5 | 5.5 |
| Average        | 1   | 1.3 | 2.2 | 3   | 3.5 | 4   | 4.3 |
| Final          | 1.3 | 1.5 | 2.2 | 2.8 | 3.7 | 3.8 | 4.5 |

Figure 3 shows the dependence of the width of the hardening track on the power of the plasma arc at different hardening distances (at a speed of 3.5 mm / s). It is seen that with increasing power and hardening distance, the width of the track increases. By analyzing the results obtained and comparing them with the results of [1-4], it is possible to draw a conclusion about the significant contribution to the geometric parameters of the hardening track of such parameters as processing speed and processing distance. Subsequently, the role of the cathode and anode spots of the plasma arc on the formation of the heating spot was evaluated according to the method described in [3,4,6-8].

Figures 4-6 show photographs taken at a welding current of 20-70 A. During hardening, it was noticed that the arc at a current of 20 A (Figure 5) burns unstably, constantly forming points with fusion, regardless of the movement of the detail, in this case, the arc lengthens, breaks, and forms a new binding, which does not give a high-quality hardened layer.

Figure 5 shows an arc at a current strength of 50 amperes. In the process of hardening, stable burning of the welding arc was observed on these parameters, no bindings with full melting were observed, the disadvantage with these parameters is small deviations. Figure 6 shows an arc at a current strength of...
70 amperes. During hardening, stable burning of the welding arc was observed on these parameters, no bindings with full melting were observed, the hardening process took place without deviations. With a further increase in the current strength to 90 A, the plasma arc burns without deviations, ensuring the stability of hardening.

![Graph showing the dependence of hardening speed on the power of the plasma arc.](image)

**Figure 3.** Dependence of the width of the hardening track on the power of the plasma arc at various hardening distances (at a speed of 3.5 mm / s).

![Photo of a snap made with force arc current 20 A.](image)

**Figure 4.** Photo of an arc snap made with force arc current 20 A.

![Photo of a heating spot made at an arc current of 50 A.](image)

**Figure 5.** Photo of a heating spot made at an arc current of 50 A.

![Photo of a heating spot performed at arc current 70 A.](image)

**Figure 6.** Photo of a heating spot performed at arc current 70 A.

The visualization of the heating spot on the metal surface according to the methodology [3,4] made it possible to further evaluate the role of anode and cathode spots on the formation of a common heating
spot in the process of plasma hardening of metals. It was established that, depending on the effective thermal power of the plasma arc [3,4], there are several modes of combustion of the plasma arc. For example, at an arc current of 20 A, there are several characteristic anode spots on the surface in the form of regular circles, which, with an increase in the arc current, contract to the center of the common heating spot. It was shown in [3,4] that the heating spot of the plasma arc has topologies that are nonuniform in temperature, which should affect the efficiency of heat input into the surface layers of the metal. In our experiments, we also fix the inhomogeneous distribution of heat along the width of the hardened track. It was shown in [5-12] that cathode spots can exert a thermal effect on a metal surface. In our experiments, cathode spots are grouped within the boundaries of the heating spot and most likely relate to spots of type 2 according to the classification of work [5,6]. It can be assumed that the type of spot will have a decisive effect on the formation of the surface layer structure and, therefore, on wear -resistance [4].

Thus, our studies have shown the importance of such technological parameters as the speed and distance of processing on the width of the hardened layer. Evaluation of the role of anode and cathode spots requires further continuation of work with the goal of revealing the general laws of the formation of a heating spot during plasma hardening.

4. Conclusion
In conclusion, the following conclusions should be noted:
1. It has been established that the speed and distance of hardening affects the width of the hardened zone during plasma surface hardening of metals.
2. The region of existence of several regimes of plasma hardening in a common heating spot was revealed, for which both single and group anode spots are characteristic.

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