Research of the technological methods influence on the formation of structure and properties during the additive growth of products from nickel chromium steels of the austenitic class by plasma-jet hard facing methods

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Abstract. The paper considers the influence of a change in the heat rate of a source with time by means of slope control, using the example of plasma-jet hard facing, as well as changes in the original structure due to laminated cool post weld upsetting of the pads, using the example of plasma-jet heat-facing with a consumable electrode (Plasma-MIG). It was found that the formation of the structure is accompanied by metal deposits transcrystallization. It is shown that the use of vibratory actions on the liquid bath by slope control modulating during plasma surfacing contributes to the partial suppression of transcrystallization of the metal deposit: the direction of columnar crystallites growth changes relative to the previous layer, contributes to the refinement of the pine-tree structure, which leads to a change in mechanical characteristics. The best properties are observed when surfacing with slope control with a frequency of 15000 Hz. The use of laminated cool post weld upsetting during the plasma-jet hard-facing by consumable electrode reduces the transcrystallization of the metal deposit. It forms dendritic crystals of an equiaxial form, which leads to the reduction of the morphological grain flow, and the strength characteristics of the fused on alloy exceed the level of the metal durability fused on without post weld upsetting and materials obtained by traditional technologies. However, the moldability characteristics remain at a high level.

1. Introduction
It is known that the production of high-quality products in additive manufacturing is provided by welding deposit technologies using highly concentrated energy sources [1, 2]. The specificity of layer growth of products in additive manufacturing requires studying the influence of technological parameters on the regularities of the formation of the weld bead, the structure and properties of the obtained material. One of the promising solutions for influencing the building up the metal proposed is to use methods of additional acting, in particular, the use of pulsed laminated plasma-jet hard-facing with the use of wire electrodes.

Welding deposit processes have one of the special meanings in a plasma materials treatment. One of the features of a plasma-jet hard-facing, which makes it differ from other methods and determines its effectiveness, includes a wide range of regulations of the plasma arc energy parameters, since it is considered as the most flexible heat source, and the plasma flow is characterized by a high temperature that makes it possible to smelt different class materials, including nickel-chrome austenitic steels. However, one should take into account the complexity of the plasma-jet hard-facing...
of austenitic steels, which is associated with their tendency to form pull cracks and dendritic segregation, while the presence of the dendritic segregation has a significant effect on the mechanical properties and corrosion resistance, and also contributes to the development of intergranular corrosion during operation [3].

In addition, the plasma-jet hard facing provides a number of technological and economic advantages: high productivity, regulation of heat transfer in a wide range and, as a result, it controls both the depth and width of a weld penetration, and structure, composition, properties of the formed material [4–6]. Consumable electrode plasma-jet hard-facing provides high stability and productivity of the surfacing process, high fusion quality due to the effect of cathodic cleaning, transfer control and absence of consumable electrode metal spattering [7, 8]. The plasma-MIG method, developed in 1972 at the Philips Research Laboratory Center (Netherlands) [9, 10], is still a relevant study [11–14].

Consumable electrode plasma-jet hard-facing (plasma-MIG) is a hybrid process that combines consumable electrode arc plasma-jet hard-facing and plasma-jet hard-facing [15–18]. The use of two sources of heating (a plasma arc from a nonconsumable anode and an arc from a consumable electrode) will allow regulating the heat input into the product in a wide range, increasing productivity and ensuring the highest quality. The axial feed of the wire electrode eliminates the use of systems for orienting the position of the wire feed relative to the welding deposit path.

The work objective is to study the influence of a change in the heat rate of a source over time by means of a slope control, using the example of the plasma-jet hard-facing, as well as changing the origin structure due to laminated cool post welding upsetting of the pads, using the example of the plasma welding with a consumable electrode (Plasma-MIG).

2. Materials and Methods
Welding wire OK Autrod 308LSi ESAB was used to obtain prototypes, the chemical composition and mechanical characteristics of the wire according to the EISO 14343-2017 standard are shown in the Table 1. The material of this chemical composition refers to a stainless steel of the austenitic class. The ferrite number of the wire is FN8 and means that the content of the ferrite phase in the welding deposit is within 3–8% (~ 4.5%).

Table 1. Characteristics of the wire 308LSi according to the EISO 14343-2017 standard.

| Chemical composition, % | C | Mn       | Si       | Cr       | Ni       | P       | S       |
|-------------------------|---|----------|----------|----------|----------|---------|---------|
| ≥ 0.03                  |   | 1.50–2.10 | 0.65–1.00 | 19.5–21.0 | 9.0–11.0 | ≥ 0.030 | ≥ 0.020 |

Yield point, σt 400 MPa 570 MPa 36%

Table 2. Plasma-jet hard-facing mode with impulse input.

| No. layers | Average current, A | Average stress, B | Argon consumption liter/min | Wire feed, meter per minute | Frequency of the impact, hertz | Plasma-forming nozzle diameter, mm |
|------------|--------------------|-------------------|-----------------------------|----------------------------|-------------------------------|----------------------------------|
| 1–15       | 210                | 26                | 2                           | 2.5                        | 0.5000.15000                 | 6                                |
| 16–25      | 186                | 25                | 2                           | 2.5                        | 0.5000.15000                 | 6                                |
| 26–46      | 157                | 22                | 2                           | 2.5                        | 0.5000.15000                 | 6                                |
The plasma-jet hard-facing with the consumable electrode was carried out by a plasmatron for Plasma-MIG welding, developed at the Welding Engineering, Metrology and Materials technology Department PNRPU in the AT-300 Hybrid Additive Manufacturing Group of Companies machining center for the introduction of hybrid additive manufacturing technology (Figure 1). Laminated forging was carried out using a SA7401H AIRPRO pneumatic hammer.

The welding deposit of the stiffening plates with interpass mechanical hardening and without deformation was carried out according to a preselected welding deposit mode: plasma arc current \( I = 120 \text{ A} \), consumable electrode arc current \( I = 210 \text{ A} \); arc voltage \( U = 23–24 \text{ V} \); wire feed speed \( V = 6.6 \text{ m/min} \); burner movement speed \( v_p = 90 \text{ cm/min} \); the volume of argon supplied to the welding torch \( Q = 7.5 \text{ l/min} \); the volume of argon supplied to the plasma-forming nozzle \( Q = 2.5 \text{ l/min} \).

![Figure 1. Machining centre AT-300.](image)

After the welding deposit of each individual bead, there was interpass mechanical hardening by cold forging. Forging was carried out according to a preselected mode: speed of the hammer \( V = 100 \text{ mm/min} \) (linear number of blows \( N/L = 28.2 \text{ blows/mm} \) at a standard frequency of a hammer blows \( N = 2820 \text{ blows/min} \); nose of a chisel - half shell in the radius \( R = 20 \text{ mm} \); an energy of a blow \( E = 19.74 \text{ J} \). The clamping force of the pneumatic hammer was 300N created by the pneumatic cylinder. The forging temperature of the pad welds was \( T = 250–300 \text{C} \).

In order to study the macro- and microstructure and mechanical characteristics of the welding deposit, blanks in the form of a plane wall were obtained. Structural studies were carried out on polished section cut in the slitting-and-shearing directions of the specimen welding deposit. Vasiliev's reagent was used to identify the macro- and microstructure. Investigations of the macrostructure were carried out on Altami CM0745-T, an optical stereomicroscope, the microstructure on Altami MET1T inverted light microscope with a magnification of up to 1000 times using the Altami Studio 3.5 software.

The phase composition of the sample was studied using an XRD-7000 X-ray diffractometer. The X-ray diffraction patterns were processed using the PANalytical XPert HighScore Plus Ver.2.1 software. The phase composition of the analyzed samples was defined using the ICDD PDF-2 + 2012 database.

The hardness measurements were performed according to the Vickers method on an automatic micro-macro-hardness tester Emco-Test Durascan 50, ser. No. 119 with a load of 100 grams. The preparation and sample testing was carried out in accordance with State All-Union standard 1497-84.

3. Results of the Study Devoted to the Effect of the Current Frequency Modulation on the Formation of the Structure and Properties During Plasma-Jet Hard-Facing

To select the frequency of the slope control, there were preliminary studies of single-roll samples [1]. One can conclude that the best results in terms of the stability of the beads formation, structure and mechanical characteristics were provided by the plasma-jet hard-facing with a current modulation on a frequency of more than 5000Hz. Further studies were carried out in the process of multiple-bead
deposit of specimens with the slope control on a frequency of 5000Hz, 15000Hz and without modulation.

The macrostructure studies showed that in the multiple-bead deposit without slope control, one can observe metal transcrystallization and the formation of long columnar grains growing through the weld pad (Figure 2, a). With slope control during welding deposit, the direction of crystallite growth was changed. Columnar grains were formed, with a length within 2 layers, i.e. less than when welding deposit without modulation (Figure 2, b, c). In all cases, the transition zone between the layers (fusion zone) is not clearly identified.

![Figure 2](image1.jpg)  
(a)  
(b)  
(c)  

**Figure 2.** Slope control, (b) – frequency 5000 Hz, (c) – frequency 15000 Hz

The microstructure has a dendritic structure. When it come to the welding deposit without slope control, there is a tendency in the microstructure to retain the crystallographic orientation between the weld pads in the weld junction (Figure 3).

![Figure 3](image2.jpg)  
(a)  
(b)  
(c)  

**Figure 3.** Microstructure of the weld deposits without slope control: (a) – the panoramic exposure, ×100; (b), (c) – the weld junction, ×500.
Figure 4. Microstructure of the weld deposits with slope control, frequency 5000Hz: (a) – panoramic exposure, ×100; (b), (c) – weld junction, ×500.

Figure 5. Microstructure of the weld deposits with the slope control on the frequency of 5000 Hz: (a) – panoramic exposure, ×100; (b), (c) – weld junction, ×500.
During welding deposit with the slope control in the weld junction, a change in the direction of dendrite crystallization was observed (Figure 4 and 5). It is demonstrated better at a slope control at the frequency of 15000 Hz. Thus, it was found that the slope control effected on the size of the dendrites themselves; the greatest milling of the dendritic structure was observed on a slope control frequency of 5000 Hz.

The X-ray phase analysis of the welded samples showed that the X-ray diffraction pattern are typical for an austenite doped with chromium and nickel (Figure 6). In the X-ray diffraction pattern of the metal obtained by welding deposits without slope control, one can observe 2 peaks. The peaks with the highest intensity corresponds to the angle of reflection from the crystallographic surface of γ-iron (220). This pattern indicates that the metal has a textured structure.

It confirms the transcrystallite character of the metal crystallization during the plasma-jet hard-facing. In the X-ray diffraction pattern of the metal obtained by welding deposit with slope control at a frequency of 5000Hz, 3 peaks are being observed, reflections occur from other crystallographic surfaces of γ-iron (111), (200) and (311). The ratio between the intensities of the diffraction peaks indicates that the metal has only a partially textured structure. The use of the slope control in the plasma-jet hard-facing does not lead to the complete elimination of the columnar structure of the dendritic structure, which is reflected in the X-ray diffraction pattern.

![Figure 6. X-ray diffraction patterns of the melted samples: 308LSi (f = 0) – welding deposits without slope control, 308LSi (f = 5000) – welding deposits with slope control, frequency 5000Hz.](image)

The hardness measurements of the melted samples were carried out in the form of three tracks run parallel at a distance of 0.2mm with a step of 0.15mm. Figure 7 shows the distribution maps of hardness values for each sample. The obtained values were used for statistical analysis, and the results are presented in the Table 3 and Figure 8. The obtained data shows that the use of the slope control leads to an increase of the welding deposit metal hardness. The highest average hardness value is observed during the surfacing with a current modulation on a frequency of 15000 Hz (above 200 kg/mm²), however, the spread in values is also the greatest one. The smallest scatter of the hardness values is observed during the welding deposit with a slope control on a frequency of 5000 Hz. Thus, it can be assumed that this type of the metal will have more homogeneous mechanical properties.
Figure 7. Micro hardness maps: (a) – without slope control, (b) – 5000 Hz frequency, (c) – 15000 Hz frequency.

Table 3. Micro hardness of melted samples obtained using different options.

|                     | The welding deposit without slope control | The welding deposit with slope control on a 5000Hz frequency | The welding deposit with slope control on a 15000Hz frequency |
|---------------------|------------------------------------------|------------------------------------------------------------|-------------------------------------------------------------|
| Average value       | 186                                      | 200                                                       | 223                                                         |
| Minimum value       | 169                                      | 182                                                       | 201                                                         |
| Maximum value       | 210                                      | 217                                                       | 250                                                         |
| Maximum value ($\bar{h}$) | 8.5                                      | 7                                                         | 12                                                         |
| Coefficient of variation ($\bar{h} \%, \%$) | 4.56                                    | 3.5                                                       | 5.38                                                       |

Figure 8. Bar charts of the microhardness value frequency distribution HV 0.1 kg/mm²: (a) – without the slope control, (b) – 5000 Hz frequency, (c) – 15000 Hz frequency.

In addition, the studies of the mechanical properties (ultimate tensile strength, yield stress, relative elongation, relative contraction, impact strength) of experimental samples were carried out depending on the conditions of the additive pre-shaping. The test pieces were cut from the workpiece at an angle of 45 degrees from the vertical. The results of a statistical processing for the values of the obtained mechanical characteristics are presented in a Table 4. Additionally (by contrast), the data of the similar alloys' mechanical properties obtained by traditional methods is being provided.
Table 4. Spread sheet of the mechanical properties.

| The type of the welding deposit, material | Resistance to rupture $\sigma_b$, MPa | Flow limit $\sigma_02$, MPa | Percentage extension $\delta$, % | Contraction rating $\psi$, % |
|------------------------------------------|--------------------------------------|---------------------------|-------------------------------|---------------------------|
| The plasma-jet hard-facing without the impulse input | 610 ± 20 | 322 ± 9 | 37 ± 5 | 55 ± 3 |
| The plasma-jet hard-facing with the impulse current input, 5000 Hz frequency | 550 ± 30 | 272 ± 7 | 47 ± 6 | 57 ± 12 |
| The plasma-jet hard-facing with the impulse current input, 15000 Hz frequency | 595 ± 3 | 285 ± 20 | 49 ± 5 | 61 ± 2 |
| Steel 04X18H10 (quenching $T = 1020$-$1100^\circ$C) | $\geq 440$ | $\geq 155$ | $\geq 40$ | $\geq 45$ |
| 04X18H10 ГОСТ 25054-81 | $\geq 441$ | $\geq 157$ | 38–40 | 45–50 |

All studied mechanical properties of the experimental samples are at the same level or above the standard material. The use of the slope control in the plasma-jet hard-facing leads to a slight decrease of the strength characteristics and an increase in plastic ones, relative to the welding deposit without modulation. The best on totality of properties is observed when welding deposit with the slope control on a 15000Hz frequency. KCU for all tested samples exceeded 200 kJ/m$^2$ regardless the vibration impact conditions.

4. Results of the Study Devoted to the Laminated Cool Forging Effect on the Structure Formation During the Plasma-Jet Hard-Facing with a Consumable Electrode

The macrostructure of the samples in the longitudinal section is demonstrated in Figure 9. During the multiple-bead deposit without laminated forging, a macrostructure of the direction metal transcrystallization is being formed. In addition, in the macrostructure of the metal, the boundaries between the layers with a thin transition zone are clearly visible (Figure 9a). In the sample macrostructure deposited with laminated forging, there are no characteristics of metal transcrystallization: for the most part, the structure is equiaxial, in some layers there are small columnar grains growing within one layer (Figure 9b).

![Figure 9](image)

Figure 9. The macrostructure of the welding deposit: (a) – deposited without laminated forging, (b) – deposited with the laminated forging.
**Figure 10.** Microstructures of the deposited metal without laminated forging:
(a) – panoramic exposure, ×100; (b), (c) – weld junction, ×500.

**Figure 11.** Microstructures of the deposited metal with the laminated forging:
(a) – panoramic exposure, ×100; (b), (c) – weld junction, ×500.
The microstructure of the welding deposits metal in both cases has a dendritic structure. When depositing without laminated forging, columnar dendrites are formed (Figure 10). In the weld junction between the layers (Figure 10 b, c), the direction of the rod-like dendrite growth of the lower layer with the upper one. A slight change in the dispersity of the microstructure is observed along the depth of the layers.

In the structure of the deposited metal with laminated forging, dendrites of equiaxial shape are formed with a small proportion of columnar dendrites in separate layers (Figure 11). At the weld junction between the layers (Figure 11 b, c), a change in the direction of dendrites growth is seen relative to the previous layer. A significant increase in the dispersion of the microstructure is observed along the depth of the layers. Comparing the microstructure inside the layer with the structure of the deposited metal without forging, one can note its significant fine crushing.

The X-ray phase analysis of the deposited samples showed that a textured metal structure is formed during the plasma consumable electrode surfacing without the laminated forging (Figure 12). The X-ray diffraction pattern has 3 highs, which with the highest intensity correspond to the angles of reflection from 2 crystallographic planes of γ-iron (220) and (311). In the diffraction pattern of the metal obtained by surfacing with the laminated forging, the peaks coincide with the angles reflection from a larger number of crystallographic surface of γ-iron. This corresponds to the polycrystalline structure of the metal (the main microstructure of the deposited metal is equiaxial dendrites).

The properties changes in the weld junction between the deposited layers were carried out by measuring the microhardness using the Vickers method. 100 measurements were made in the form of a 5–20 grid: 5 measurements in width with a step of 0.1mm and 20 measurements in depth with a step of 0.05mm. The measurements were made capturing the areas of the lower and upper layers. Based on the measurement results, there were built maps of hardness changes and the statistical processing of the obtained measurements was carried out. The results are presented in Figure 13 and in Table 5. The hardness distribution maps (Figure 13) are showing the lines indicating the weld junction; depth values (h) with the “–” sign corresponding to the lower layer, and the “+” sign corresponding to the upper layer.

According to the presented results, one can notice that using the laminated cool forging, the total hardness level is being increased by 50 HV units, however, a more homogeneous hardness is being observed in the case of welding deposit without forging.
Table 5. Microhardness of the samples obtained using different options

|                              | The welding deposits | The welding deposits with laminated deformation |
|------------------------------|----------------------|-----------------------------------------------|
| Average value                | HV 0.1 kg/mm²        | 201.36                                        |
| Minimum value                |                      | 250                                           |
| Maximum value                |                      | 180                                           |
| Maximum value (f)            |                      | 217                                           |
| Coefficient of variation (J, %) |                     | 3.56                                          |
|                              |                      | 11.35                                         |
|                              |                      | 7.16                                          |
|                              |                      | 4.54                                          |

According to the presented results, one can notice that using the laminated cool forging, the total hardness level is being increased by 50 HV units, however, a more homogeneous hardness is being observed in the case of welding deposit without forging.

![Microhardness maps](image1)
![Flow chart](image2)

Figure 13. Microhardness maps of the intermix between layers (a, b) and flow chart of the microhardness values frequency distributions (c, d): (a), (b) – surfacing without hammering; (b), (d) – surfacing with the laminated hammering; h – the measurements along the depth of the layer, (b) – the measurements along the width of the layer.

The results of the mechanical characteristics of the deposited metal using various options obtained during pulling test are presented in the Table 6. For testing, there were used four samples from the cross-section of the deposited workpieces. In the table, for comparison, were added the requirements for the mechanical properties of similar alloys obtained by the traditional methods.

The test results showed that when products are manufactured using additive technology by surfacing Plasma-MIG metal with and without laminated forging, the mechanical characteristics exceed the requirements for products obtained by traditional methods from steels of this class. The use
of the laminated cool forging leads to an increase of the strength characteristics, while maintaining the plastic characteristics at a high level, in comparison with Plasma-MIG surfacing without forging.

**Table 6.** Testing results on the mechanical properties.

| Production process                          | Resistance to rupture $\sigma_b$, MPa | Flow limit $\sigma_{0.2}$, MPa | Percentage extension $\delta$, % | Contraction rating $\Psi$, % |
|---------------------------------------------|--------------------------------------|--------------------------------|---------------------------------|-----------------------------|
| Plasma-MIG surfacing                        | 555 ± 10                             | 300 ± 20                       | 36 ± 5                          | 46 ± 5                      |
| Plasma-MIG surfacing with laminated cool forging | 720 ± 40                             | 560 ± 70                       | 30 ± 3                          | 50 ± 10                     |
| Steel 04X18H10 (quenching $T = 1020–1100 \, ^{\circ}\text{C}$) | $\geq 440$                           | $\geq 155$                     | $\geq 40$                       | $\geq 45$                   |
| 04X18H10 ГОСТ 25054-81                       | $\geq 441$                           | $\geq 157$                     | 38–40                           | 45–50                       |

5. Conclusion

As a result of the study devoted to the metal structure formation during the plasma-jet hard-facing and the plasma-jet hard-facing with consumable electrode (Plasma-MIG), it was found that the formation of the structure is accompanied with the transcrystallization of the deposited metal. Due to that, long columnar grains are formed, extending through several layers. The crystallizing columnar dendrites retain a certain crystallographic orientation, and, hence, the deposited metal has a textured structure.

The use of the vibration action on the liquid bath by modulating the current during the plasma surfacing contributes to the partial suppression of the transcrystallization of the deposited metal: the direction of the columnar crystallites growth changes relatively to the previous layer. Thus, the columnar dendrites retain their definite directionality within the deposited layer. In addition, the use of the slope control during surfacing leads to the dendrite structure refinement. These changes in the structure impact on the mechanical characteristics: when it comes to the plasma surfacing with slope control, there is a slight decrease in the strength characteristics and an increase in plastic ones, compared to surfacing without modulation. The best properties are observed when the surfacing with slope control using frequency of 15000 Hz.

The use of the laminated cool forging in the consumable-electrode plasma-jet hard-facing makes it possible to eliminate the transcrystallization of the deposited metal. In the structure of the deposited metal, the dendrites of an equiaxial shape, leading to the elimination of the structural texture, are being formed. The use of forging in surfacing contributes to an increase in the fineness of the microstructure. The result is that, the strength characteristics of the deposited alloy exceed the level of the metal deposited strength without forging and there are materials obtained by traditional technologies. At the same time, the plasticity characteristics stay at a high level.

Acknowledgements

This research was funded by Russian Science Foundation (RSF), grant number 21-19-00715 “Control of microstructure, strength, residual stresses and geometry distortions in hybrid additive manufacturing” (Agreement No. 21-19-00715 dated 20.03.2021).

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