Intelligent diagnostics and control of 3D printing processes by electric arc surfacing of workpieces made of cold-resistant materials on a CNC machine using machine learning approaches and neuromorphic calculations

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Abstract. The article discusses a method for diagnosing and optimizing the dynamic state of an electric arc during 3D printing of workpieces from cold-resistant materials on a CNC machine within the framework of a cyber-physical system. The possibility of applying nonlinear dynamics methods to assess the stability of the 3D printing process and artificial neural processes for classifying and optimizing the parameters of the dynamic state of the 3D printing process is shown. Experimental studies of the cold resistance obtained by 3D printing of 09G2S steel samples were carried out taking into account the choice of optimal modes.

1. Introduction
The active development of the territories of the Arctic and the Far North in the Russian Federation necessitates the creation of new special-purpose technical facilities capable of operating at extremely low temperatures for a long time. When developing the design of such objects, much attention is paid to the choice of cold-resistant materials with the corresponding physical and mechanical characteristics.

Considerable experience has already been accumulated in the field of studying the cold resistance and damage to various groups of materials at low temperatures. Recommendations on their choice depending on operating conditions were obtained, and the temperature of the viscous-brittle transition was determined for a wide range of metals [1,2]. However, these studies, as a rule, apply only to cold-resistant materials obtained by traditional methods (casting, rolling, etc.).

At present, additive technologies are widely used in the field of production of parts and assemblies of complex shapes [3], including the so-called hybrid technologies, including 3D printing with subsequent mechanical processing without reinstalling the part on one processing center [4-8]. The most popular 3D printing technologies are laser fusion of metal powders (SLM), laser powder surfacing (DMD) and electric arc welding (WAAM), while the latter two are considered the most versatile and able to integrate into CNC machines with the lowest conversion costs [6]. This approach allows to significantly reduce the technological chain of procurement and increase the flexibility of the enterprise in a single and small-scale production. This is especially true for solving a wide range of service and production problems in the Arctic and the Far North, where it is often necessary to produce unique parts of complex shape from cold-resistant materials for the repair of various technical objects as soon as possible.

However, studies show that at the moment there are a number of unresolved issues that limit the use
of hybrid technologies that combine 3D printing with electric arc surfacing and subsequent machining [4-8]. In particular, there is no information on assessing the influence of the modes and conditions of 3D printing by electric arc welding on the composition, structure and properties, and, accordingly, on the indicators of cold resistance of materials. There are no mathematical models of 3D printing processes that allow predicting and controlling the properties of cold-resistant materials both in the process of electric arc surfacing and at the stage of technological preparation of production. Moreover, studies show that the stability of the surfacing process plays a decisive role in ensuring the desired properties of the workpieces, in particular, dynamic processes in an electric arc that determine the conditions of droplet formation and transfer of electrode material, crystallization zones, and chemical transformations in the material. It is also necessary to take into account the fact that the dynamic hybrid processing system is a complex, nonlinear dissipative system, unstable chaotic oscillations of the electric arc and the elastic system of the machine can arise in it, which greatly complicate the assessment of the current and forecasting the future state by traditional mathematical methods.

Thus, the scientific problem associated with the diagnosis and control of the dynamic processes of 3D printing by electric arc welding and the subsequent mechanical processing of workpieces of complex shapes from cold-resistant materials at CNC machining centers remains unresolved.

The solution to this problem is possible through the development of science-based methods of digital modeling and hardware and software for intelligent forecasting and classification of the dynamic state of 3D printing processes of complex blanks from cold-resistant materials using the principles of artificial intelligence, machine learning and nonlinear dynamics [4,5,8].

2. Software implementation

To solve the indicated problem, an experimental stand (Figure 1) of hybrid processing was developed and manufactured [6]. The test bench includes a portal type CNC machine, a MIG 200 electric arc cladding system, an SC145-600 electric arc current sensor, an SV025 electric arc voltage sensor, a GT200 acoustic emission sensor, an NI 6356 and NI 9205 analog-to-digital converter, and a collection bus NI data cDAQ-9188, pyrometer, for temperature control in the print zone, and a PC for data collection and processing.

![Figure 1](image)

Figure 1. An experimental bench for 3D surfacing on the basis of a CNC machine (1 - 3 coordinate coordinate machine with portal type CNC), 2 - a broadband acoustic emission sensor GT350, 3 - a PC with a wireless access system to the Microsoft Azure cloud service, 4 - power sensors current and voltage, 5 - ADC / DAC, 6 - CNC system, 7-welding semiautomatic device, 8 - Microsoft Azure cloud service, 9 - shielding gas cylinders)

In figure 2 shows a sample of the workpiece and the finished part after machining at the developed stand.
Data collection in the process of experimental research was carried out as part of the industrial Internet of things network emulator and the Microsoft Azure cloud storage and data processing service. This approach subsequently made it possible to implement a full-fledged statistical analysis of experimental data with an ever-increasing dimension. During the experiment, metal samples were printed on the machine from 09G2S steel with the transfer of electrode material by a short circuit.

As variable parameters, the modes of electric arc surfacing were adopted: current strength, voltage, arc gap, wire feed speed and shielding gas flow rate. Informative sources about the dynamic state of the 3D printing process were oscillograms in the form of time series of changes in the actual current strength, voltage, and acoustic emission.

In connection with the above, the main diagnostic parameter characterizing the degree of stability of the dynamic system “power source – arc – material” was the indicator of the fractal dimension of the attractor of the VAE signal. Reconstruction was carried out on the basis of the time series of current, voltage and VAE signals, using the Tackens theorem and calculating the correlation integral. The use of the index of fractal dimension of an attractor is determined by the need to assess the degree of randomness of processes and trajectories of formative movements due to the presence of nonlinear links in the technological system. At the same time, for digital signal processing, bandpass digital and Wavelet filters were used. The use of Wavelet filters made it possible to minimize the influence of the noise component in VAE signals and carry out decomposition on the periodic and chaotic component based on entropy indices [8].

3. Experimental studies
A unique feature of the developed experimental stand was the ability to conduct experimental studies fully automatically. For this, a PC feedback channel with a CNC system and a semiautomatic welding machine was implemented. According to a previously developed algorithm, a search harmonic signal was supplied to the circuit of the control system of the welding semiautomatic device along three channels: “voltage”, “current strength”, “wire feed speed” A similar signal was fed to and to the CNC system through the control channels of the machine feed drive along the X axes and Z. This search signal also periodically changes in phase throughout the entire surfacing process. This approach made it possible to obtain a large combination of print modes in various ranges and a corresponding dynamic picture. At the same time, all current values of operating modes and indications of fractal dimension were recorded in the corresponding database rows on the Microsoft Azure cloud service.

At the end of printing, a visual inspection of the deposited metal layers was performed. During the visual inspection, the type of defect and its coordinates were determined. The main types of defects identified were: metal sprays, fistulas, pores, uneven weld widths, incrustations and macrocracks. Each of the identified defects was assigned a number. All defect numbers were recorded in additional database columns and tied to the corresponding signal values and processing modes. Analysis of the experimental
data, showed the decisive influence of surfacing modes on the dynamic state of a 3D printing system.

From figure 3 it can be seen that under certain conditions there is a loss of stability of the process of electric arc surfacing and the transition of the system to chaotic dynamics. In this case, the main scenarios of the transition to chaos were: the transition through intermittency, doubling the period and beating. Thus, with the intelligent management and diagnostics of 3D printing processes, the early detection and prediction of such scenarios is relevant. As can be seen from figure 3b, the transition of the system to chaotic dynamics is accompanied by rearrangement of the attractor, and accordingly its fractal dimension changes. The restructuring of the attractor of the system leads to a change in the kinetics of all phases of the state of the arc-material system, the parameters of the processes of heat and mass transfer, melting and crystallization of the material, chemical transformations, and heat-affected zones change.

![Attractor of a stable arc](image1.png)  
![Attractor in case of loss of stability](image2.png)

**Figure 3.** 3D printing system attractors: a) attractor of a stable arc b) attractor in case of loss of stability

Therefore, we can conclude that the appearance of chaotic dynamics makes predictable control of the surfacing process impossible, and, accordingly, it is impossible to guarantee the required material structure and its cold resistance. This circumstance is especially relevant for structures operating in conditions of extremely low temperatures and high dynamic loads.

In the course of research, it was found that the indicator of fractal dimension of the attractor is the most sensitive parameter to the emergence of scenarios of transition to chaotic dynamics. As can be seen from Fig. 3 b, c, during the reconstruction of the attractor of the dynamic system, a change in the fractal dimension occurred. So, for a relatively stable arc, the fractal dimension of the attractor was $D_f = 3.1$, and when the system switched to chaotic dynamics, the fractal dimension increased to $D_f = 3.8$. As part of the research, these attractors were obtained on the basis of the time series of the change in current strength, and a time window of 30,000 samples was used. I take into account the sampling frequency of the signal, this size of the time window corresponds to 1 second of the process.

Despite the rather high information content of the current values, when assessing the stability of the system, additional control of the melting and crystallization of the material during a short circuit is necessary. As can be seen from fig. 4 values of current and voltage can be accurate markers of the beginning and end of a short circuit, the transfer time of the metal, the energy expended, and, accordingly, the amount of heat in the print zone. However, during the contact of the electrode material with the substrate, their information content decreases. To improve the quality of diagnostics, an acoustic emission signal was additionally used. The operating frequency of the broadband AE sensors makes it possible to capture various features of micrometallurgical processes during the contact of the electrode metal with the base metal. Therefore, an indicator of the fractal dimension of the attractor reconstructed based on the AE signal was used as an additional diagnostic parameter for the stability of 3D printing processes.
4. Analysis of the results of experimental studies

Given the large amount of statistical data, an apparatus of artificial neural networks was chosen for the implementation of diagnostic systems for 3D printing processes with cold-resistant materials [6,7]. In the process of research, the ANN architecture was used (Fig. 5) and studies were conducted on the dynamic state of processes on sensors (current sensor, voltage sensor, and acoustic sensor). The input of the obtained neural network is a vector of data showing that the short-circuit pulses are received with a time shift. This approach made it possible to use the history of dynamic events to assess the stability of the system, identify scenarios of loss of stability, and classify defects. The output from the neural network is 2 neurons, which are responsible for the class of defects and the degree of stability. A neural network is determined by the degree of stability: stable, unstable and loss of stability. Microsoft Azure Neural network training takes place using statistical selection. In the formation of training the choice of neural network models were used [9] data mining methods.

This approach is necessary for patterns and trends in large volumes of continuously incoming data. Typically, such patterns cannot be detected by traditional statistical analysis. In particular, the following data mining technologies were applied: neural network clustering and data classification (self-organizing maps of Kokhonna and nearest neighbors), exploratory data analysis (exploratory data analysis), for studying statistical properties, estimation of model parameters and their diagnostics using numerical re-sampling methods (cross-validation (cross) s-validation, CV), bootstrap), analysis of the optimal combinations of them, ranking of several alternative models and adjusting their most important x parameters. After the training process, the neural classification network (Fig. 5) was downloaded using a cloud service to a PC.

![Figure 4. Oscillograms of current, voltage and acoustic emission signal during 3D printing by electric arc welding on a CNC machine.](image)

![Figure 5. Artificial neural network for the classification of the dynamic state of 3D printing processes.](image)
Given the time that the material transfer processes take place, the required minimum response time in the diagnosis of the dynamic stability of the hybrid processing system. The hardware implementation was obtained by a neural network model based on the neuroprocessor NM 500 from Neuro Mem, made using 110 nm technology, and combining 576 neurons. The case dimensions of this processor are 4x4 mm (WCSP64), and the consumption is less than 153 mW in active mode. The NM500 requires an external control processor that will provide neural data. In this case, communication is carried out on a parallel bi-directional 26-bit bus. In fact, the NM500 is a chain of identical neurons that are interconnected. The NM500 is capable of operating in two main modes: learning and recognition. We can talk about completely different in nature data.

To integrate the NM 500 neuroprocessor into the telemetry data acquisition and processing system, a special Neuro Shield debug board was used. This board allows the neuroprocessor to interact with the integrated FPGA via a 28-pin data bus. This board also has I2C and SPI protocols for exchanging data with external devices (IIoT). In this case, the device was used on the Raspberry Pi platform. An additional advantage of using this debug board is the scaling of a neuromorphic system by adding neuroprocessors to a single system using the Neuro Brick expansion platform. Each optional Neuro Brick board provides integration of two NM500 neuroprocessors. Using this approach to the diagnosis of the dynamic state of processes. 3D printing provides high-precision classification of multidimensional time series of the sensor system in real time.

Testing of the obtained diagnostic system was carried out based on the selection of optimal modes and control of the surfacing process in the manufacture of experimental samples. To select the optimal modes, the obtained ANN was used (Fig. 5). At the same time, this ANN worked in deconvolution mode using the back propagation method of error. The essence of the method is to select the necessary state of the output neurons, fix the weight coefficients of the intermediate layers and automatically adjust the weights of the input layer. As part of the study, the output values of neurons were selected as “stable” and “0”, which corresponds to the absence of defects. Then the initialization of the neurons of the input layer took place, until the learning error became minimal. At the end of the balance adjustment, time series of current, voltage, and acoustic emission were obtained based on the given stability conditions. After, the obtained time series were passed through an existing database on a cloud service using the correlation function. By the maximum of the correlation function, the closest composition of the time series in the database and the corresponding modes were determined. Thus, the optimal surfacing modes were selected corresponding to the most stable process.

Using the obtained modes, experimental samples were made. Samples were milled without reinstalling on this machine. Then, the microstructure of the obtained samples was evaluated for comparison with billets obtained from rolled products. As can be seen from fig. 6, there are certain differences between the structures of steel 09G2S obtained by different methods.

![Figure 6](image)

Figure 6. Microstructures of steel 09G2S:
- a) obtained by rolling and past annealing,
- b) obtained by electric arc welding.

Thus, the structure formed by the method of electric arc welding is finer-grained than the structure
of steel obtained by rolling. This is a consequence of the specific thermal effects during the 3D printing process. In general, a fine-grained structure is preferable from the point of view of cold resistance, however, the features of grain boundaries having certain discontinuities are visible in the images, which can lead to a change in the physical properties of the material.

The results of tensile tests of samples made of 09GS steel, obtained on the basis of 3D printing on a CNC machine using the technology of electric arc surfacing and subsequent machining are presented in table 1. The results of tensile tests (table 1) show that the mechanical characteristics of 09G2S steel obtained by electric arc surfacing slightly differ from similar samples obtained by classical methods, and in some cases they exceed them in tensile strength and yield strength. The mechanical properties of samples cut in different directions of surfacing (along and across) also differ slightly. The direction of application of the load to a greater extent affects the elongation (Table 1), which is 18% more in the case of cutting samples along the direction of surfacing.

| Mechanical indicators, MPa | $\delta,\%$ | $\sigma_{0.2},\MPa$ | $\sigma_b,\MPa$ |
|--------------------------|----------------|--------------------|----------------|
| Samples cut along the direction of surfacing | 27 | 361 | 506 |
| Samples cut across the weld direction | 22 | 352 | 502 |
| Samples obtained by machining from sheet metal | 23 | 325 | 490 |

The results of impact bending tests are shown in Figure 7. An analysis of the obtained dependences of the toughness on the test temperature of the studied classes of samples shows that the nature of the change in the toughness of the samples obtained by electric arc surfacing and the machining of rolled metal coincides. For samples obtained by electric arc welding, the values of impact strength are 15 ... 20% lower than the values of impact strength of samples obtained by machining from annealed sheet metal over the entire range of temperatures studied.

![Figure 7](image.png)

**Figure 7.** The results of tests for impact bending of steel samples 09G2S: 1 - from sheet metal with subsequent annealing; 2 - cut along the direction of surfacing; 3 - cut across the direction of surfacing.

5. Conclusion

Thus, we can conclude that the selected 3D printing modes fully satisfy the requirements for the structure of materials operating at extremely low temperatures, and the use of ANN is possible both for classifying the dynamic state in real time and for optimizing surfacing modes.
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