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Investigation of changes in geometrical parameters of GMAW surfaced specimens under the influence of longitudinal magnetic field on electric arc

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ABSTRACT

Introduction. The paper presents the results of research of additive manufacturing process by electric arc with axial feeding of steel filler wire in protective gas environment (*GMAW* technology) with additional influence of external longitudinal magnetic field on electric arc. **Purpose of work:** an experimental study of the effect of a longitudinal magnetic field during additive manufacturing by an electric arc with axial feed of filler wire made of structural steels in a shielding gas environment on the change in the geometrical characteristics of the layers being surfaced. **Research Methods.** The manufacturing of specimens was carried out on a 5-axis additive machine based on a *CNC* machine. Surfacing was carried out in the following modes: voltage 17.5 V; current 55–65 A; wire diameter 1.2 mm; wire material *Sv-08G2S*; wire feed rate 2,267 mm/min; approximate roll diameter 3.0 mm; roll length 50 mm; number of wires per one roll 312.5 mm; number of layers when surfacing the wall 5; magnet operation mode: alternating current with frequency 50 Hz, voltage 30 V; measured magnetic induction 5.7 mTl; initial height of the magnet above the substrate 10 mm; electrode stickout 10 mm; shielding gas: welding mixture CO_2-*Ar*; gas pressure (flow rate) 0.15 MPa. **Results and discussion.** The conducted experimental study showed that the effect of longitudinal magnetic field had a statistically significant effect on the change in the dimensions of the singular, namely an increase in the width of the layers being surfaced by 34.1 %, with a calculated significance index close to zero, and a decrease in height by 20.2 %, with a calculated significance index equal to 2.7×10^{-5}. The effect of longitudinal magnetic field had a statistically significant effect on the change of the overall dimensions of the specimens consisting of five layers, namely, the width of the specimens increased by 11.2 % with a calculated significance index of 4.3×10^{-3}, and the height of the specimens decreased by 10.3 % with a calculated significance index of 6.3×10^{-5}. The effect of longitudinal magnetic field had no statistically significant effect on the change of the vertical deviation from straightness for the side walls of the specimens, with a calculated significance index of 0.3277, and had no statistically significant effect on the change of the error of the width of the walls of the specimens, with a significance index of 0.098.

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Introduction

Currently, additive manufacturing technologies for products based on starting material melting are widely used; among it, we can put emphasis on the *GMAW* technology, or the technology of additive manufacturing using an electric arc with axial feeding of a filler wire made of various metals in shielding gas environment. This technology is characterized by high productivity in shaping products and has wide versatility, which explains a great interest in its use in various industries, and is the main reason for a large number of scientific works in this area [1–7]. The main factors hindering the expansion of the scope of application of this technology are quite low accuracy of the fabricated parts characterized by large

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shape deflection (sometimes more than 10 mm), as well as the non-uniform structure of the material of the resulting products, which negatively affects physical and mechanical properties of materials and, as a consequence, finished products performance characteristics [1–7]. One of the directions of research in this area is the implementation of the surfacing process when an electric arc is additionally exposed to an external magnetic field, which can be traditionally divided into longitudinal [8–18] and transverse [19–29] ones, which has found its application in improving the quality of the processes of various types of electric arc welding and surfacing. In many studies, it was found that under the influence of a magnetic field, the rate of wire melting increases, the microstructure improves, the depth and area of the fusion zone decreases, which has a positive effect on the quality of welded joints [8–29]. It was also noted in [8, 12, 14, 16, 18] that a longitudinal magnetic field causes an arc column to rotate around its axis and to contract, reducing the cross-section of the arc column; the arc becomes harsher, and heating is more concentrated, which improves the technological properties of the arc and improves the quality of welding process and welds.

However, despite the positive effect of a longitudinal magnetic field on the quality of welding, the analysis of papers in the area under consideration has shown that the process of additive shaping by an electric arc with axial feeding of steel filler wire in a shielding gas environment, in particular, with additional influence of the longitudinal magnetic field on the electric arc has been studied insufficiently [30–35].

In particular, the issue of changes in the geometry of single surfaced layers and specimens formed in this way using a wire made of structural steels has not been sufficiently studied.

Therefore, the ***purpose of this work*** is to study experimentally the influence of a longitudinal magnetic field during additive shaping by an electric arc with axial feeding of a filler wire made of structural steel in shielding gas environment on changes in the geometry of the surfaced layers, namely, changes in the dimensions of single surfaced layers, changes in the overall sizes of the specimens, consisting of several layers, changes in the deflection from straightness in vertical direction for the side walls of the specimens and changes in the deflection in the width of the specimen walls.

Research methods

To conduct this study, the Department of Mechanical Engineering Technologies and Equipment of Southwest State University, developed a machine based on a *CNC* machine equipped for implementing *GMAW* technology or the technology of additive shaping of products by an electric arc with axial feeding of a filler wire in a shielding gas environment (Fig. 1).

The developed machine consists of a sequential kinematic chain, which includes an aluminum base (frame) (**1**), with linear guides (**2**) fixed on it, along which, by means of a ball screw and stepper motors (**3**) a *CNC* machine table (**4**) with a rotary table (**5**) located on it are driven along the *X* axis (*X* coordinate), *Z* axis module (**6**) is driven along the *Y* axis (*Y* coordinate), and a feeding mechanism (**7**) is driven along the *Z* axis (*Z* coordinate). The rotary table provides rotation of a workpiece about the *Y* axis (angular coordinate *B*) and rotation of a workpiece about the *Z* axis (angular coordinate *C*). The machine is controlled using a control unit (**8**), which includes an *Arduino Mega 2560* control board with the *Ramps 1.6* add-on (*grbl-Mega-5X* firmware), six *TB 6600* stepper motor drivers, a 12 V 30 A power supply. *GrblGru_v5.1.0* open-source software is used to implement control programs. The developed installation provides simultaneous 5-axis surfacing (5-axis continuous processing). The feeding mechanism (**7**) consists of a stepper motor, a clamp and steel rollers that feed the welding (surfacing) wire from the coil (**9**) through the steel tube to the welding head into the welding (surfacing) zone. An electromagnet (**10**) is attached to the welding head. The semi-automatic *KEDR MIG-160GDM* welding machine was used as a power source.

The study of the influence of a longitudinal magnetic field on changes in the geometry of the surfaced layers was carried out by surfacing a wire of 1.2 mm in diameter made of *Sv-08G2S* (0.08 % *C*; 2 % *Mn*; 1 % *Si*). In accordance with the methodology described in [26], for this wire the surfacing conditions were as follows: 17.5 V (voltage); 55 A (current); 2,267 mm/min (wire feeding speed); an approximate roller diameter was 3.0 mm; the length of a roller was 50 mm; wire length per roller was 312.5 mm; electrode extension was 10 mm; CO_2-*Ar* welding mixture was used as a shielding gas; gas pressure (flow) was 0.15 MPa.

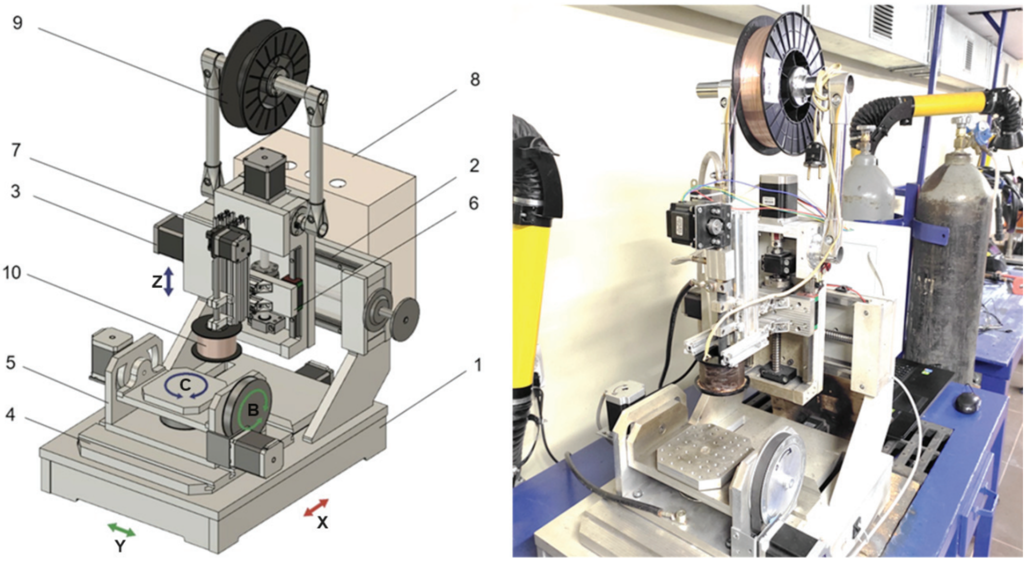
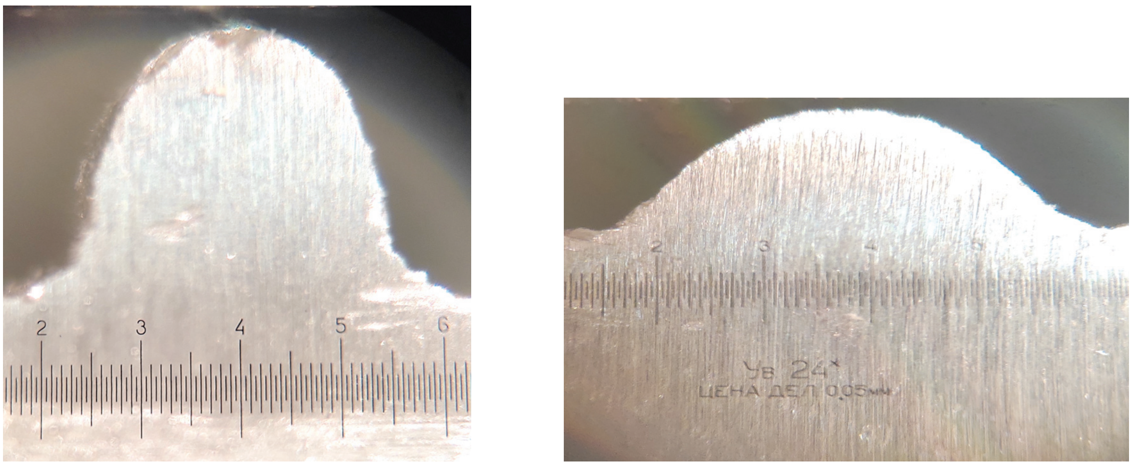


Fig. 1. Machine for wire-arc additive manufacturing on the basis of *CNC* machine:

1 – frame; *2* – linear guides; *3* – stepper motor; *4* – *CNC* machine table; *5* – rotary table; *6* – Z-axis module; *7* – feeding mechanism; *8* – control unit; *9* – coil; *10* – electromagnet

To create a longitudinal magnetic field, an electromagnet was used; its steel core had an internal diameter of 20 mm, a wall thickness of 4 mm; a winding was made of *PETV-2* wire with a diameter of 0.72 mm with a number of turns of 1,200. Preliminary, it was found out experimentally that the surfacing process runs stably when the electromagnet is connected to an alternating sinusoidal current with a frequency of 50 Hz and a voltage of 30 V; the initial height of the magnet above the backing was 10 mm, so further, surfacing of specimens was carried out in these modes. The measurement carried out using a portable universal *TPU* milliteslameter showed that under these modes of applying electromagnet at a melting point of the wire, the magnetic induction does not exceed 5.7 mT.

When studying the influence of a longitudinal magnetic field on the dimensions of single layers, six specimens were surfaced: three specimens were deposited without the influence of a longitudinal magnetic field and three ones were surfaced when the electric arc was exposed to a magnetic field created by an inductance coil. The surfaced specimens were cut in three places and preliminarily cleaned along the cut plane. The dimensions of single layers, its width and height, were measured using an *MPB-2* microscope at 24-fold magnification with a scale value of 0.05 mm (fig. 2).



a *b*

Fig. 2. Cross-section of single surfaced layers:

a – without longitudinal magnetic field; *b* – with longitudinal magnetic field

Results and discussion

The results of measuring the dimensions of single surfaced layers are given in Table 1.

The processing of the obtained data when studying the influence of the longitudinal magnetic field on the measurements of the width and height of single surfaced layers was carried out in the *Statistica* program based on the calculation of the *t*-test for independent samples (fig. 3).

From the results obtained, it follows that the effect of the created magnetic field caused a statistically significant change in the dimensions of single surfaced layers, so the layer width increased by 34.1 % (the value of the calculated *t*-test is –9.585 and the probability that the width of the layers does not differ is close to zero $p \approx 0$); the height of the surfaced layer decreased by 20.2 % (the value of the calculated *t*-test is 5.799 and the probability that the height of the layers does not differ is $p \approx 2{,}7\times10^{-5}$). Furthermore, the table (see fig. 3, *a*) presents the results of the calculation of *F*-criterion, on the basis of which we can conclude that

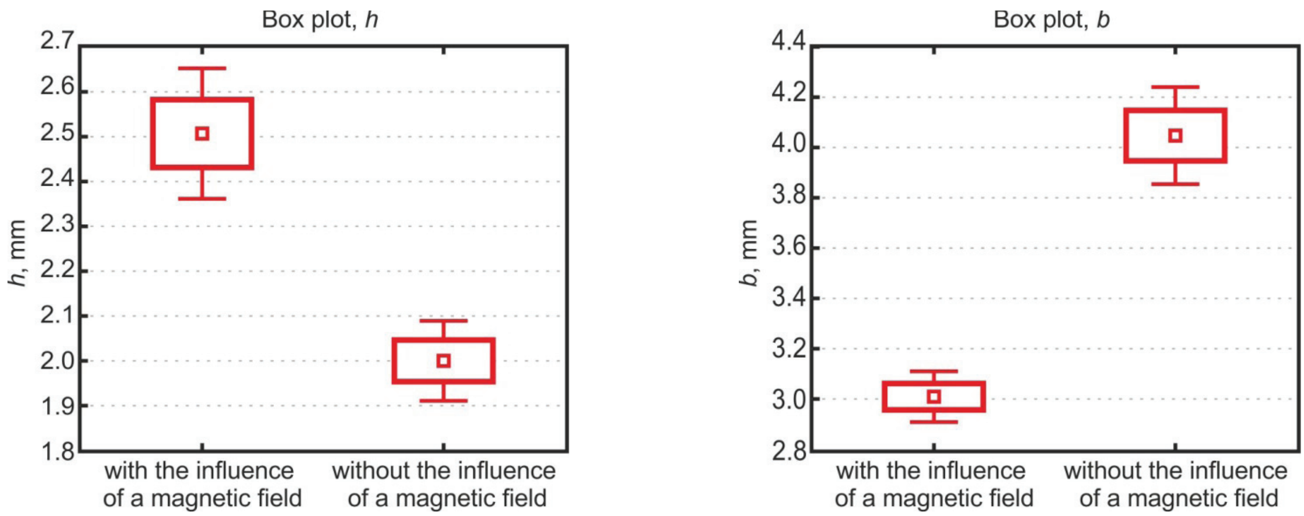
Table 1

Results of measuring the dimensions of single surfaced layers, mm

without the influence of a magnetic field	width	3.00	3.00	3.10	2.90	3.10	3.30	3.00	2.80	2.90
	height	2.85	2.25	2.50	2.50	2.20	2.30	2.70	2.70	2.55
under the influence of a magnetic field	width	4.40	4.40	4.20	3.65	3.70	4.20	4.10	3.80	3.90
	height	1.80	2.00	2.05	1.95	2.00	2.20	2.20	1.85	1.95

Variable	t-test, Group, Data table 1 Group 1:2 Group 2:1 Mean 2	Mean 1	t	cc	p	Rank 2	Rank 1	Stat.dev. 2	Stat.dev. 1	F-relative variance	p variance
b	3.011111	4.038889	−9.58536	16	0.000000	9	9	0.145297	0.286986	3.901316	0.071411
h	2.505556	2.000000	5.79900	16	0.000027	9	9	0.222829	0.136931	2.648148	0.189944

a



b *c*

Fig. 3. Analysis of the effect of a longitudinal magnetic field on the change in dimensions of single surfaced layers:

a – table of the results of *t*-criterion calculation; *b* – box plot for the height of a single layer; *c* – box plot for the width of a single layer the size dispersions of single surfaced layers are statistically insignificant; so, the calculated F-criterion for width dispersions is 3.9, with a calculated significance index of 0.0714, and the F-criterion for height variances is 2.65, with a calculated significance index of 0.1899; the calculated significance indices exceed the accepted significance level of 0.05.

To study the influence of a longitudinal magnetic field on the change in overall dimensions and geometric error of the surfaced layers, six specimens consisting of five vertical layers were surfaced: three specimens were surfaced without the influence of a longitudinal magnetic field and three ones were surfaced when the electric arc was exposed to a magnetic field created by an inductance coil (fig. 4).

The overall dimensions of the surfaced specimens were assessed based on the parameters of the maximum width and height in the sections under consideration. Fig. 5 shows a diagram of measuring the maximum width (b_{max}) and height (h_{max}) of the surfaced specimens without exposure to a longitudinal magnetic field (fig. 5, *a*) and exposed to a longitudinal magnetic field (fig. 5, *b*).

Table 2 presents the results of measuring the overall dimensions of the surfaced specimens.

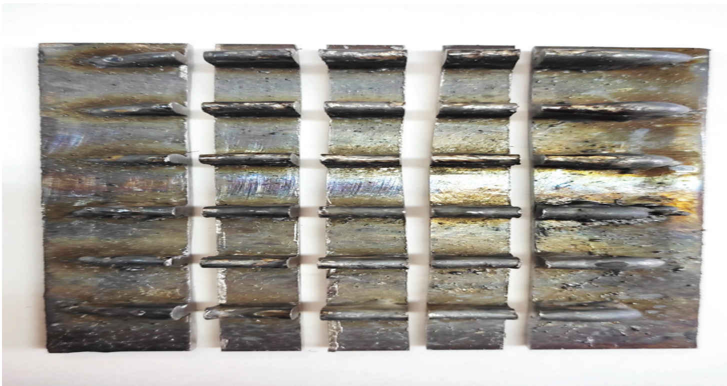
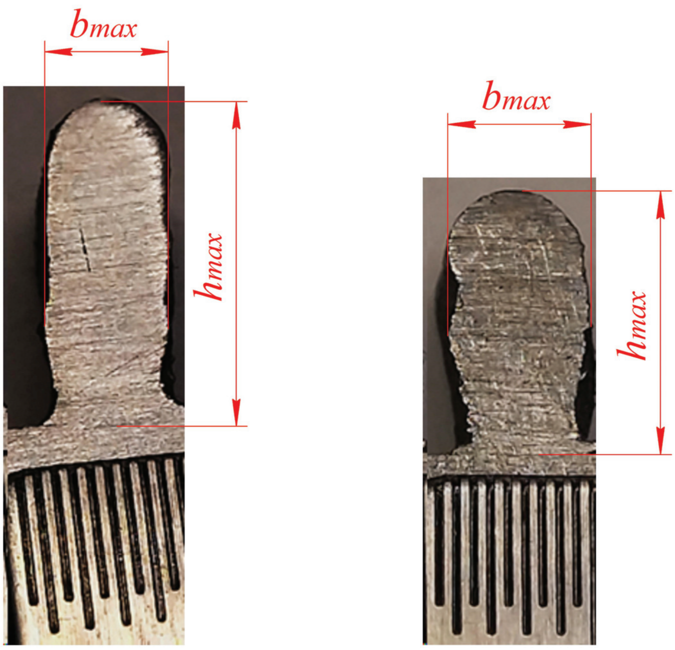


Fig. 4. Surfaced and cut specimens consisting of five layers



a *b*

Fig. 5. Scheme for measuring the greatest width and height of the specimens surfaced:

a – without influence of a longitudinal magnetic field; *b* – with influence of a longitudinal magnetic field

Table 2

Results of measuring the greatest width and height of the surfaced specimens

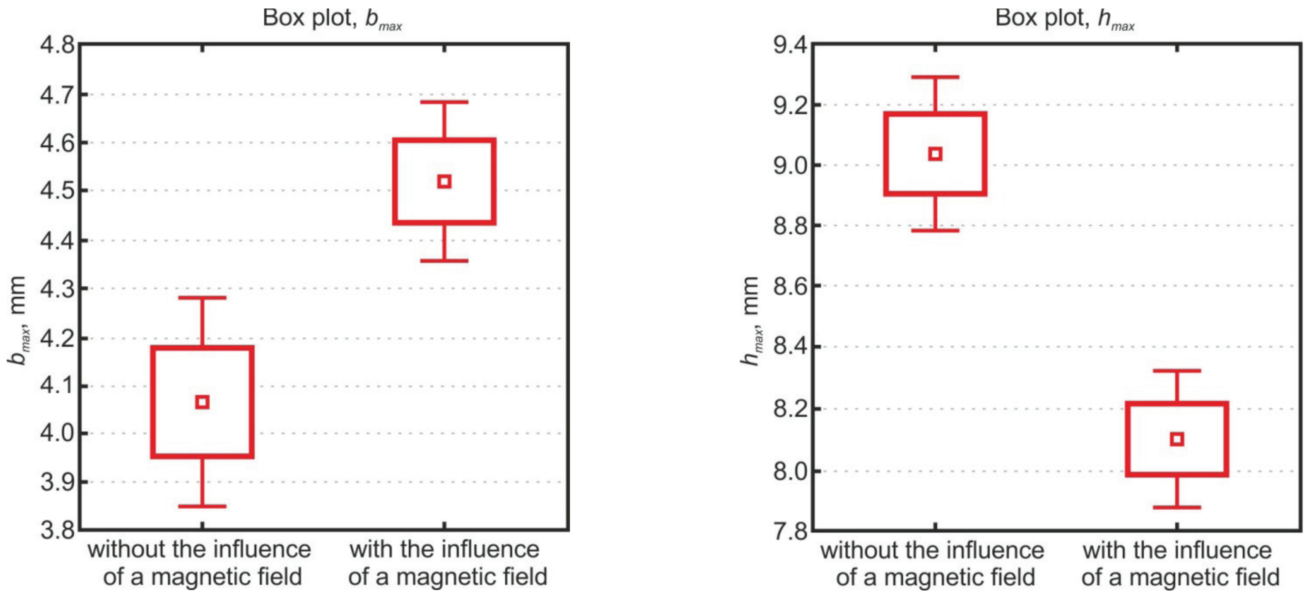
	Specimen					
	1	2	3	4	5	6
	without exposure to a magnetic field			exposed to a longitudinal magnetic field		
	b_{max}, mm					
Section 1	4.7	4.2	3.7	4.3	5.1	4.5
Section 2	4.3	3.8	3.7	4.7	4.4	4.5
Section 3	4.2	4.1	3.9	4.4	4.3	4.5
	h_{max}, mm					
Section 1	9.0	8.7	9.3	8.1	8.4	7.6
Section 2	8.8	8.3	9.3	8.1	8.4	8.2
Section 3	9.2	9.1	9.6	7.9	8.6	7.6

The results of calculating the *t*-test for independent samples based on the results of measuring the overall dimensions of the surfaced specimens (see Table 2) are presented in fig. 6.

t-test, Group, Data table 5
Group 1:1
Group 2:2

Variable	Mean 1	Mean 2	t	cc	p	Rank 1	Rank 2	Stat.dev. 1	Stat.dev. 2	F-relative variance	p variance
b_{max}	4.066667	4.522222	−3.32008	16	0.004332	9	9	0.327872	1.735426	1.735426	0.452583
h_{max}	9.033333	8.100000	5.36383	16	0.000063	9	9	0.387298	0.350000	1.224490	0.781478

a



b *c*

Fig. 6. Results of the analysis of the influence of the longitudinal magnetic field on the change of the overall dimensions of the surfaced specimens:

a – table of *t*-criterion calculation results; *b* – box plot for the width of the specimens; *c* – box plot for the specimens' height

From the results obtained it follows (see fig. 6) that the overall dimensions of the specimens, consisting of five layers surfaced without applying a magnet, have a statistically significant difference from the dimensions of the specimens, surfaced under the influence of a magnetic field; namely, the width of the specimens increased by 11.2 %, with a calculated *t*-criterion equal to –3.22 and a significance index of 4.3×10^{-3}, and the height of the samples decreased by 10.3 %, with a calculated *t*-criterion equal to 5.36 and a significance index of 6.3×10^{-5}. The results of the calculation of *F*-criterion (see fig. 6, *a*) showed that the variances of the overall dimensions of the surfaced specimens are statistically insignificant and the calculated significance indices exceed the accepted significance level of 0.05.

The change in the geometric error of the surfaced layers was assessed by the value of deflection from straightness of the specimen's side walls in vertical direction for a given section as well as the deflection in the width of the specimen. Fig. 7 shows a diagram for measuring the value of deflection from straightness, which was carried out for the left wall (EFL_1) and the right wall (EFL_2) of the specimen, and in further calculations the deflection from straightness having the largest value was used:

$$EFL = \max\,(EFL_1, EFL_2).$$

The results of measuring deflection from straightness are presented in Table 3.

Fig. 8 shows the results of a statistical comparison of the value of the deflection from straightness using *t*-test.

From the obtained results (see fig. 8) it follows that deflections from straightness in vertical direction for the side walls of the specimens surfaced without a magnet do not have a statistically significant difference from the specimens surfaced under the influence of a magnetic field, with the calculated *t*-test criterion equal to –1.0097 and a significance index of 0.3277, which exceeds the accepted significance level of 0.05. Based on the value of the calculated *F*-criterion, the variance of the deflection from straightness of the side walls of the surfaced specimens is also statistically insignificant, with a calculated significance index of 0.3496.

To compare the deflection values of the specimens' wall width, for each specimen the width was measured at seven points of different heights, according to the diagram presented in fig. 9.

Table 4 shows the results of measuring the width of the surfaced specimens.

a *b*

Fig. 7. Scheme for measuring the deviation from straightness of the specimens surfaced:

a – without the influence of a longitudinal magnetic field; *b* – under the influence of a longitudinal magnetic field

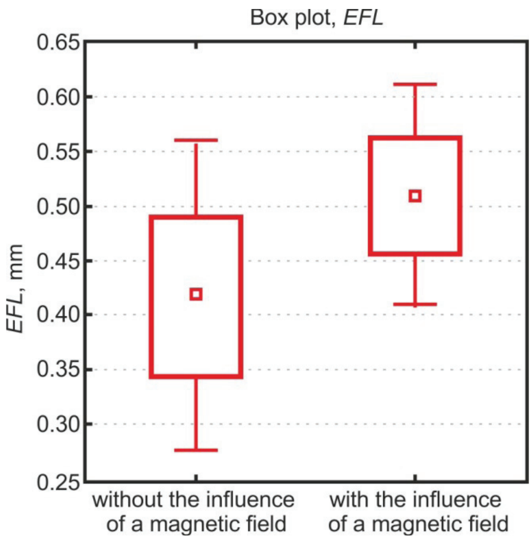
Table 3

Results of measuring the deviation from straightness of the side walls of the specimens in the vertical direction for a given section

Specimen		Section	EFL_1, mm	EFL_2, mm	EFL, mm
without the influence of a longitudinal magnetic field	1	1	0.24	0.19	0.24
		2	0.38	0.22	0.38
		3	0.48	0.41	0.48
	2	1	0.25	0.77	0.77
		2	0.13	0.17	0.17
		3	0.25	0.58	0.58
	3	1	0.18	0.14	0.18
		2	0.68	0.17	0.68
		3	0.2	0.29	0.29
under the influence of a longitudinal magnetic field	4	1	0.24	0.31	0.31
		2	0.24	0.3	0.3
		3	0.08	0.44	0.44
	5	1	0.28	0.53	0.53
		2	0.64	0.55	0.64
		3	0.77	0.15	0.77
	6	1	0.47	0.21	0.47
		2	0.34	0.48	0.48
		3	0.45	0.65	0.65

Variable	t-test, Group, Data table 7 Group 1:1 Group 2:2										
	Mean 1	Mean 2	t	cc	p	Rank 1	Rank 2	Stat.dev. 1	Stat.dev. 2	F-relative variance	p variance
EFL	0.418889	0.510000	−1.00968	16	0.327677	9	9	0.220876	0.156525	1.991270	0.349589

a



b

Fig. 8. Results of the analysis of the influence of the longitudinal magnetic field on the change of deviation from straightness of the side walls of the surfaced specimens in the vertical direction: *a* – table of *t*-criterion calculation results; *b* – box plot of deviations from straightness

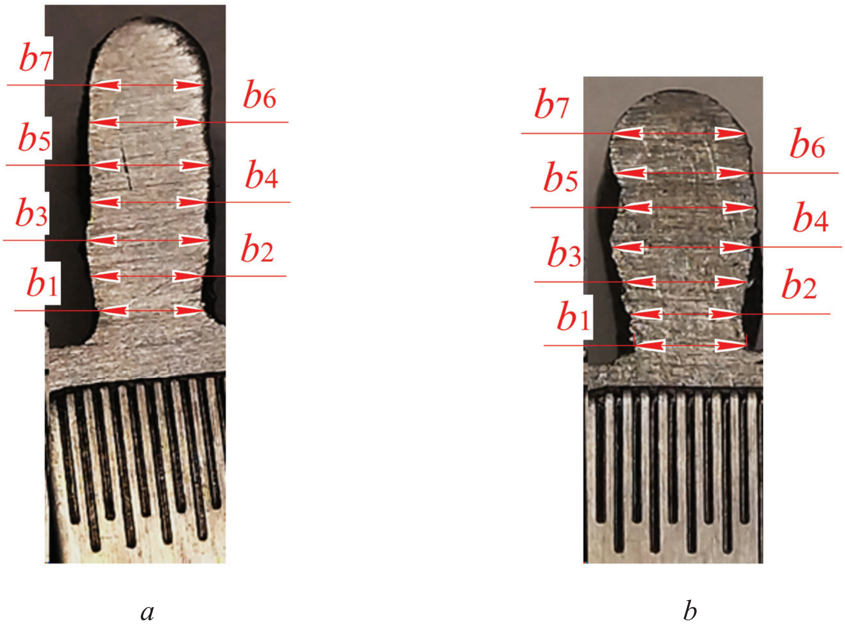


Fig. 9. Scheme for measuring the width of the surfaced specimens:
a – without the influence to a longitudinal magnetic field; *b* – under the influence of a longitudinal magnetic field

Table 4

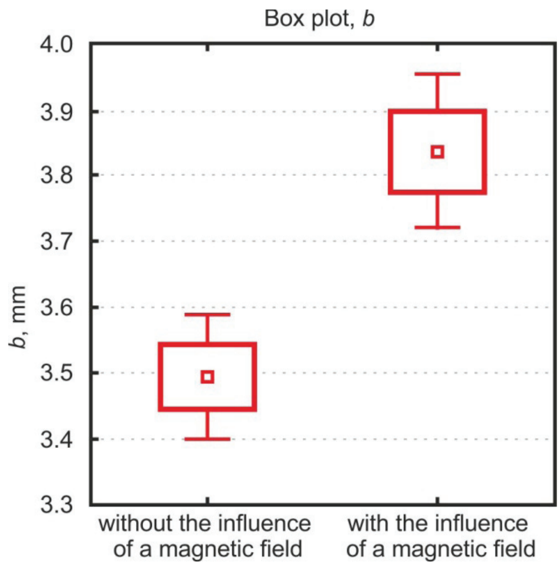
Results of measuring the width of the surfaced specimens at various points

Specimen		Section	width (b_i), mm						
			1	2	3	4	5	6	7
without the influence of a longitudinal magnetic field	1	1	3.47	3.47	3.59	3.65	3.75	3.86	3.50
		2	2.88	3.35	3.63	3.76	4.01	3.95	3.06
		3	2.89	3.61	3.97	4.16	4.15	4.07	3.40
	2	1	2.89	3.51	3.81	3.99	4.06	3.99	3.74
		2	3.46	3.46	3.61	3.74	3.74	3.46	2.51
		3	3.16	3.64	3.70	3.85	3.85	3.58	2.67
	3	1	3.38	3.51	3.51	3.54	3.54	3.45	3.07
		2	2.83	3.32	3.58	3.70	3.70	3.48	2.87
		3	3.12	3.26	3.30	3.27	3.28	3.26	2.69
under the influence of a longitudinal magnetic field	4	1	4.95	4.13	3.83	3.52	3.86	4.09	3.70
		2	4.16	4.08	4.06	3.89	3.95	3.69	2.95
		3	4.95	4.08	3.83	3.75	4.05	4.19	3.13
	5	1	5.06	4.67	4.00	4.13	3.93	3.78	3.61
		2	3.65	3.78	3.61	3.63	3.82	3.70	2.99
		3	2.96	3.44	3.78	3.99	4.05	3.92	3.03
	6	1	3.78	4.00	3.85	3.85	3.85	3.60	2.87
		2	3.43	3.48	4.14	4.19	4.13	4.10	3.11
		3	2.97	3.52	4.29	4.42	4.29	4.23	3.31

To perform the analysis, a comparison of the variances in the width of the specimens surfaced without exposure to a magnetic field and when exposed to a magnetic field was made using *F*-criterion (fig. 10).

Variable	t-test, Group, Data table 9 Group 1:1 Group 2:2										
	Mean 1	Mean 2	t	cc	p	Rank 1	Rank 2	Stat.dev. 1	Stat.dev. 2	F-relative variance	p variance
b	3.496190	3.837778	−4.49016	124	0.000016	63	63	0.379811	0.469411	1.527467	0.097940

a



b

Fig. 10. Results of analysis of the influence of the longitudinal magnetic field on the walls width error of surfaced specimens:

a – table of *F*-criterion calculation results; *b* – box plot of deviations

From the obtained results (see fig. 10) it follows that the deflection in the width of the walls of the specimens surfaced without exposure to a magnetic field and when exposed to a longitudinal magnetic field is statistically insignificant, the value of the calculated *F*-criterion is 1.5275 with a significance index of 0.098, which exceeds the accepted significance level.

Conclusion

The conducted experimental study of the geometry of the surfaced specimens showed that exposure to a longitudinal magnetic field:

– caused a statistically significant change in single dimensions; namely an increase in the width of the surfaced layers by 34.1 % with a calculated significance index close to zero, and a decrease in the height by 20.2 % with a calculated significance index equal to 2.7×10^{-5};

– caused a statistically significant change in the overall dimensions of the specimens consisting of five layers; namely, the width of the specimens increased by 11.2 % with a calculated significance index of 4.3×10^{-3}, and the height of the specimens decreased by 10.3 % with a calculated significance index of 6.3×10^{-5}.

– did not have a statistically significant effect on the change in the deflection from straightness in vertical direction for the specimens' side walls with a calculated significance index of 0.3277.

– did not have a statistically significant effect on the change in the deflection in the width of the specimens' walls, with a significance index of 0.098.

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Conflicts of Interest

The authors declare no conflict of interest.