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Anisotropy of properties in metal materials fabricated by wire arc additive manufacturing (WAAM)

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ABSTRACT

Introduction. Additive manufacturing (*AM*) technologies, particularly wire arc additive manufacturing (*WAAM*), offer a rapid and cost-effective approach for producing complex metal components. However, *WAAM* can induce anisotropy in the resulting material's physical and mechanical properties. This anisotropy must be considered in design and application to ensure reliable performance in service. **The purpose of the work.** This study aims to quantitatively assess the anisotropy of mechanical properties in materials produced by *WAAM* to enhance the reliability of components used in critical applications. **Research methodology.** Samples were fabricated from low-carbon alloyed steel (0.08 *C*-2 *Mn*-1 *Si*), stainless steel (0.04 *C*-19 *Cr*-9 *Ni*), and aluminum alloy (97 *Al*-3 *Mg*) using the *WAAM* process. These samples were then subjected to mechanical testing to determine their tensile and impact toughness and hardness. Results were compared to those of the materials in the initial state to determine the relative anisotropy of each property. **Results and discussion.** For 0.08 *C*-2 *Mn*-1 *Si* steel, the tensile strength of *WAAM*-fabricated samples exhibited minimal variation across different orientations, indicating relatively high isotropy (relative anisotropy of 1.3 %). A relative anisotropy of 33 % was observed for elongation, 21 % for impact toughness, and 16 % for hardness. The 0.04 *C*-19 *Cr*-9 *Ni* stainless steel exhibited a relative anisotropy of 15.1 % for tensile strength, 244 % for elongation, 33 % for impact toughness, and 4% for hardness. The 97 *Al*-3 *Mg* aluminum alloy showed a significant relative anisotropy in tensile strength (83.6 %) and relative elongation (513 %) due to differences in the "vertical" direction. Impact toughness exhibited only slight variations (28 %) depending on sample orientation, while hardness can be considered isotropic. In general, hardness demonstrated the lowest relative anisotropy, while elongation exhibited the highest.

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Introduction

Currently, additive technologies (*AT*) open up new possibilities for manufacturing complex metal products. Wire arc additive manufacturing (*WAAM*) combines the advantages of welding technologies and additive manufacturing. The *WAAM* method uses a standard welding arc and filler wire [1]. In the *WAAM* process, an electric arc melts the wire, which then deposits layer by layer, forming the desired part or component. The advantages of using the *WAAM* method are high deposition speed, the ability to manufacture large-sized parts, and relative cost-effectiveness [2]. However, like many AT based on layer-by-layer deposition of material, *WAAM* technology leads to the formation of anisotropy of the physical and mechanical properties of the synthesized materials [3, 4]. This is crucial for the practical application of such a technology in the creation of critical, complexly loaded components.

Anisotropy in materials obtained by the *WAAM* method is a consequence of the specific thermodynamic conditions of the process. One of these conditions is directional heat input, namely, when the arc successively melts the wire, creating local volumes of melt (weld pools) that quickly solidify. This leads to the formation of a pronounced columnar-dendritic microstructure [5], usually oriented upward from the substrate or previous layer, and radially from the center of the bead [6]. Another condition is the inherent characteristics of the layer-by-layer deposition process, which creates a layered macrostructure with boundaries between beads and layers. These boundaries can be zones with altered chemical composition, grain size, defect density, and residual stresses. Along the boundaries of beads or layers, the resulting defects (pores and lack of fusion) can have an elongated shape and a preferred orientation [7]. Also, during deposition, the synthesized material experiences complex thermal cycles, since each newly deposited layer subjects the underlying layers to multiple heating and cooling, which leads to recrystallization, grain growth, phase transformations in previously deposited layers, as well as the development of significant residual stresses due to uneven heating and cooling [8].

Studies have shown that when using *WAAM* technology for various alloys, the mechanical properties of the resulting materials, such as tensile strength and relative elongation, often depend on the manufacturing direction. As a rule, these characteristics are higher in the horizontal direction compared to the vertical one [9]; the difference varies depending on the material and can reach significant values [10–12]. However, there are technological modes that allow for relatively isotropic behavior [13]. In addition, for some alloys, such as magnesium *AZ31*, the opposite tendency is observed – the best mechanical properties are revealed in the vertical direction [14], which also indicates a pronounced anisotropy of the structure and properties of products obtained by the *WAAM* method.

The ability to direct the properties of a material in the desired direction allows us to optimize the product and enhance its operational performance.

To control the anisotropy of the synthesized material properties by the *WAAM* method, a whole range of measures is used, for example:

– selection of modes with reduced heat input [15];

– use of pulsed or *CMT* (cold metal transfer) modes to reduce the volume of the weld pool and thermal effects [16];

– application of strategies that change the deposition direction to disrupt the columnar structure [17];

– preliminary and concomitant heating of the substrate [18];

– heat treatment to relieve stress, homogenize the structure, and achieve the required set of properties [19];

– application of surface plastic deformation after (shot blasting) or during synthesis (ultrasonic treatment, rolling, impact forging, wave strain hardening) of each or several layers to refine the grain and break down the columnar structure, reduce porosity, and create compressive residual stresses on the surface [20].

The purpose of this work is to quantitatively evaluate the anisotropy of mechanical properties of materials synthesized by wire arc additive manufacturing (*WAAM*). To achieve this purpose, the following ***tasks*** were addressed during the study:

– synthesis of first-order samples from three materials commonly used in mechanical engineering, exhibiting significantly different technological and mechanical properties: low-carbon alloy steel 0.08 *C*-2 *Mn*-1 *Si*, stainless steel 0.04 *C*-19 *Cr*-9 *Ni*, and aluminum alloy 97 *Al*-3 *Mg*, using *WAAM*;

– cutting out second-order samples from the synthesized first-order samples, with specific orientations relative to the direction of both feedstock feed and *WAAM* synthesis, to assess the mechanical properties;

– characterization of the mechanical properties of the synthesized material in several directions, including tensile strength, relative elongation, impact toughness, and hardness;

– comparison of the mechanical properties of the synthesized material with those of the original material (rolled product), determination of the relative anisotropy for each property parameter, and analysis of the relationship between the level of anisotropy and the material grade, synthesis direction, and feedstock supply.

Methods

To predict the reliability and optimize the process of achieving isotropic or controlled-anisotropic properties, it is essential to study the anisotropy of the mechanical properties of materials obtained by the *WAAM* method. For this purpose, the following properties were analyzed: tensile strength, tensile relative elongation, impact toughness, and hardness of various materials with significantly different technological and mechanical properties that are commonly used in *AT*: low-carbon steels, stainless steels, and aluminum alloys. Specific samples from each category were selected for the analysis: low-carbon alloy steel 0.08 *C*-2 *Mn*-1 *Si*, stainless steel 0.04 *C*-19 *Cr*-9 *Ni*, and aluminum alloy 97 *Al*-3 *Mg*.

The concept of ‘relative anisotropy’ is proposed, which enables a quantitative assessment of not only the variation of properties in different directions within the material synthesized by the *WAAM* method (classical anisotropy), but also the deviation of these properties in characteristic directions from the known values reported in the reference literature for rolled products of the same material grade – the ‘original material’. This approach allows for the following:

– to evaluate the influence of the *WAAM* synthesis direction and feedstock movement direction on the homogeneity of the material properties in the volume of the synthesized product and on the deviation of the material properties of the synthesized sample from the properties of rolled products of the same material grade, as well as the heterogeneity of these deviations depending on the characteristic direction within the synthesized volume;

– to identify critical directions where the deviation of properties from the original material is the most significant;

– to provide an integral assessment of the suitability of the material and technology for critical applications; for instance, a high (especially negative) value of relative anisotropy in any direction for a key property signals a potential weakness of the structure in that direction.

The relative anisotropy of the ultimate strength of the synthesized samples compared to the ultimate strength of the material in its initial state was estimated as:

$$\Delta\sigma_u = \frac{\sigma_{u0} - \sigma_u}{\sigma_u} \cdot 100\,\%,$$

where σ_{u0} and σ_u are the ultimate strength values, with σ_{u0} representing the ultimate strength of the material in its initial state and σ_u representing that measured in the synthesized samples, in MPa.

The relative anisotropy of the tensile relative elongation of the synthesized samples compared to the tensile relative elongation of the material in its initial state was estimated as:

$$\Delta\varepsilon = \frac{\varepsilon_0 - \varepsilon}{\varepsilon} \cdot 100\,\%,$$

where where ε_0 and ε are the tensile relative elongation values, with ε_0 representing the tensile relative elongation of the material in its initial state and ε representing that measured in the synthesized samples, in %.

The relative anisotropy of the impact toughness of the synthesized samples compared to the impact toughness of the material in its initial state was estimated as:

$$\Delta KCU = \frac{KCU_0 - KCU}{KCU} \cdot 100\,\%,$$

where KCU_0 and KCU are the impact toughness values, with KCU_0 representing the impact toughness of the material in its initial state and KCU representing that measured in the synthesized samples, in J/cm² (or equivalent unit), with the calculated anisotropy expressed as a percentage.

The relative anisotropy of the hardness of the synthesized samples compared to the hardness of the material in its initial state was estimated as:

$$\Delta HV = \frac{HV_0 - HV}{HV} \cdot 100\,\%$$

where HV_0 and HV are the hardness values, with HV_0 representing the hardness of the material in its initial state and HV representing that measured in the synthesized samples, in HV.

If $\Delta\sigma_u$, $\Delta\varepsilon$, ΔKCU, ΔHV are positive, then the corresponding characteristics (σ_u, ε, KCU, HV) of the material synthesized by the *WAAM* method are inferior to those of the original material. If the values are negative, then the characteristics of the *WAAM* material are superior. The total relative anisotropy for the first-order samples was calculated as the difference between the maximum and minimum values of the relative anisotropy values obtained from the second-order samples.

To conduct the research, first-order samples in prism form were synthesized using the *WAAM* method, from which second-order samples were cot out for tensile strength tests according to *GOST 1497-84*, impact toughness tests according to *GOST 9454-78*, and for Vickers hardness measurements. To conduct strength and impact toughness tests, the samples were positioned within the synthesized prisms as shown in Figs. 1 and 2.

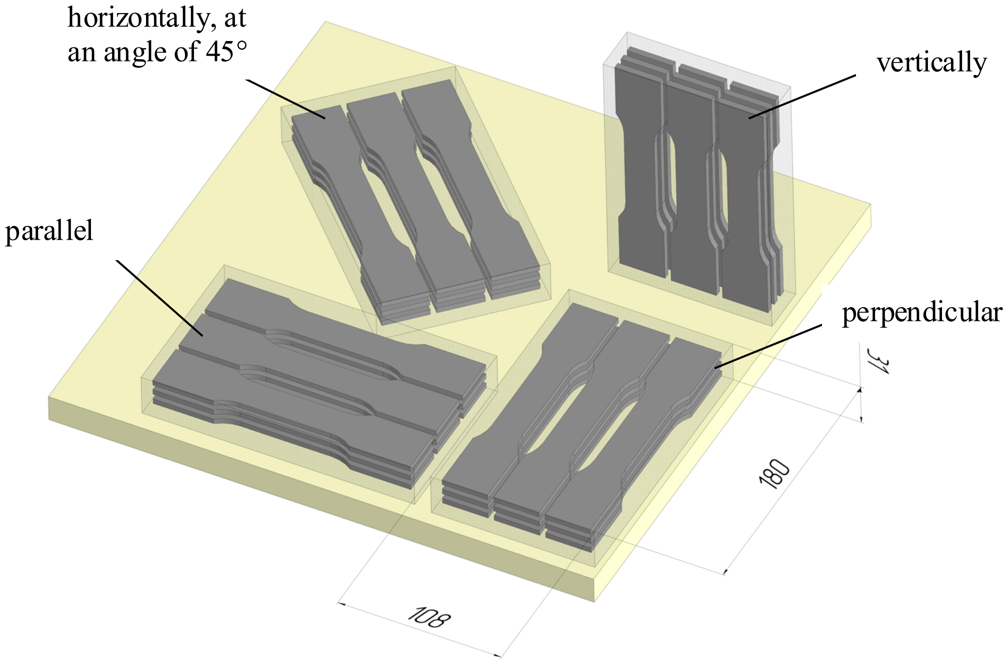

Fig. 1. Schematic representation of synthesized samples arrangement on the substrate (welding torch direction consistent for all samples)

The second-order samples were manufactured in the vertical direction (the synthesis direction) and three horizontal orientations: parallel to the feedstock feed direction, perpendicular to it, and at an angle of 45°. Hardness measurements were performed in three planes: vertical, parallel, and perpendicular to the feedstock feed direction (Fig. 3).

Hardness measurements were performed with a step of 0.3 mm over a 10 mm base. In each direction, at least three parallel series of such measurements were conducted. For each level (consisting of at least three measurement points), the average hardness value was calculated. The height of each synthesized layer for 0.08 *C*-2 *Mn*-1 *Si* and 0.04 *C*-19 *Cr*-9 *Ni* steels was 2.2 mm; for the 97 *Al*-3 *Mg* aluminum alloy, it was 2.5 mm.

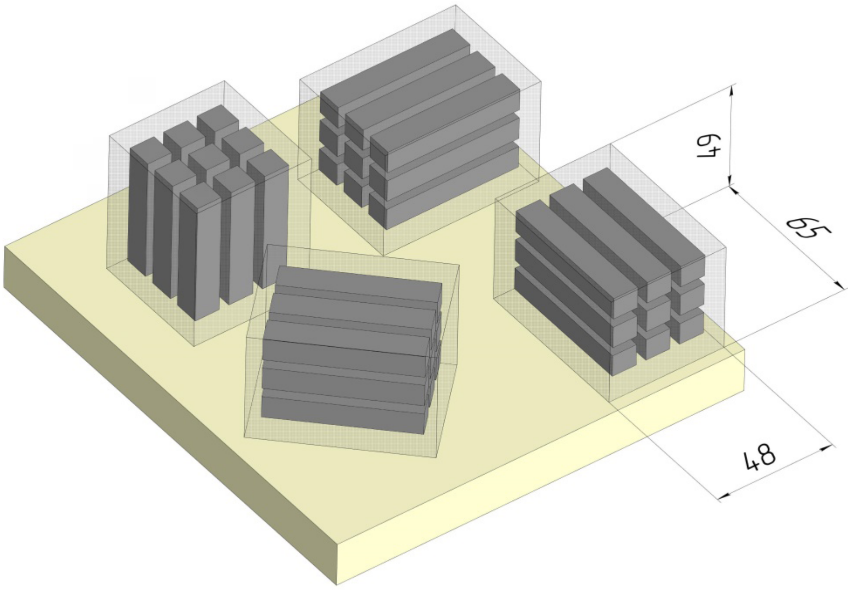

Fig. 2. Schematic representation of synthesized sample arrangement for impact toughness testing on the substrate (welding torch direction consistent for all samples)

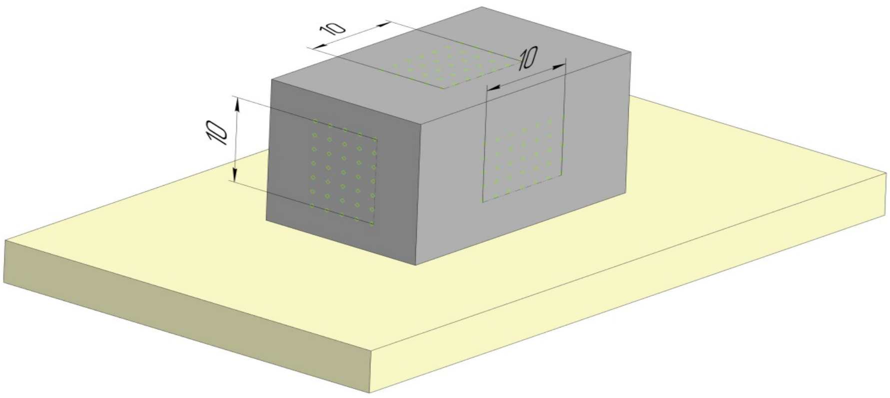

Fig. 3. Hardness measurement scheme for synthesized samples

The synthesis modes were selected based on the conditions for obtaining high-quality samples with a minimum number of pores (Table 1) [21].

Table 1

Synthesis parameters

Parameter	Material		
	0.08 *C*-2 *Mn*-1 *Si*	0.04 *C*-19 *Cr*-9 *Ni*	97 *Al*-3*Mg*
Current, A	175	170	125
Voltage, V	19.6	18.3	18.7
Wire feed rate, m/min	5.64	6.37	7.3
Feedstock feed rate, mm/min	1,000	1,000	1,000
Wire diameter, mm	1.2	1.2	1.2

Results and Discussion

It was found that for 0.08 *C*-2 *Mn*-1 *Si* steel, the ultimate strength of samples obtained by the *WAAM* method is practically the same in all directions of orientation, measuring 486–492 MPa (Table 2), and is practically not inferior to the ultimate strength of rolled products in the delivered condition (490–510 MPa). The ultimate strength relative anisotropy was 1.3% (Fig. 4, *a*). Based on this parameter, the synthesized material can be considered isotropic. The relative elongation of the "vertically" positioned sample is slightly lower compared to the horizontally positioned sample, at 12% and 13%, respectively, and is significantly inferior to the relative elongation values of rolled products made from this material in the delivered condition (20–30%). The relative elongation relative anisotropy was 33% (Fig. 4, *b*).

The maximum impact toughness value of 192 J/cm² was recorded on samples with the "horizontal, at an angle of 45°" cutting direction, while the minimum (154 J/cm²) was observed for samples with the "perpendicular" cutting direction (Table 2). This exceeds the impact toughness of rolled products made of this material in the delivered condition (130–162 J/cm²). The impact toughness relative anisotropy was no more than 21% (Fig. 4, *c*).

Table 2

Mechanical properties of synthesized materials

Material	Property	Second-order sample position within the prism	Sample cutoff direction relative to feedstock feed direction	Source material (rolled stock)	*WAAM*-fabricated material	Relative anisotropy, %
0.08 *C*-2 *Mn*-1 *Si*	σ_u, MPa	vertically	–	500	486	2.9
		horizontally	at a 45-degree angle		490	2.0
			perpendicular		492	1.6
			parallel		487	2.7
	ε, %	vertically	–	25	10.8	131
		horizontally	at a 45-degree angle		12.6	98
			perpendicular		12.6	98
			parallel		12.6	98
	KCU, J/cm^2	vertically	–	146	166	−12
		horizontally	at a 45-degree angle		192	−24
			perpendicular		154	−5
			parallel		168	−13
	HV, kgf/mm^2	vertically	–	190	212	−10
		horizontally	perpendicular		179	6
			parallel		202	−6
0.04 *C*-19 *Cr*-9 *Ni*	σ_u, MPa	vertically	–	620	534	16.1
		horizontally	at a 45-degree angle		614	1.0
			perpendicular		537	15.5
			parallel		562	10.3
	ε, %	vertically	–	35	22	56
		horizontally	at a 45-degree angle		16.7	110
			perpendicular		9	300
			parallel		20.1	74
	KCU, J/cm^2	vertically	–	120	177	−32
		horizontally	at a 45-degree angle		125	−4
			perpendicular		119	1
			parallel		141	−15
	HV, kgf/mm^2	vertically	–	190	355	−47
		horizontally	perpendicular		318	−40
			parallel		336	−43

The End Table 2

Material	Property	Second-order sample position within the prism	Sample cutoff direction relative to feedstock feed direction	Source material (rolled stock)	*WAAM*-fabricated material	Relative anisotropy, %
97 *Al*-3 *Mg*	σ_u, MPa	vertically	–	230	129	78.3
		horizontally	at a 45-degree angle		230	0
			perpendicular		243	−5.3
			parallel		220	4.5
	ε, %	vertically	–	13	2	550
		horizontally	at a 45-degree angle		8.55	52
			perpendicular		9.03	44
			parallel		9.47	37
	KCU, J/cm^2	vertically	–	40	17	134
		horizontally	at a 45-degree angle		16	145
			perpendicular		18	117
			parallel		18	128
	HV, kgf/mm^2	vertically	–	45	74	−39
		horizontally	perpendicular		74	−39
			parallel		73	−39

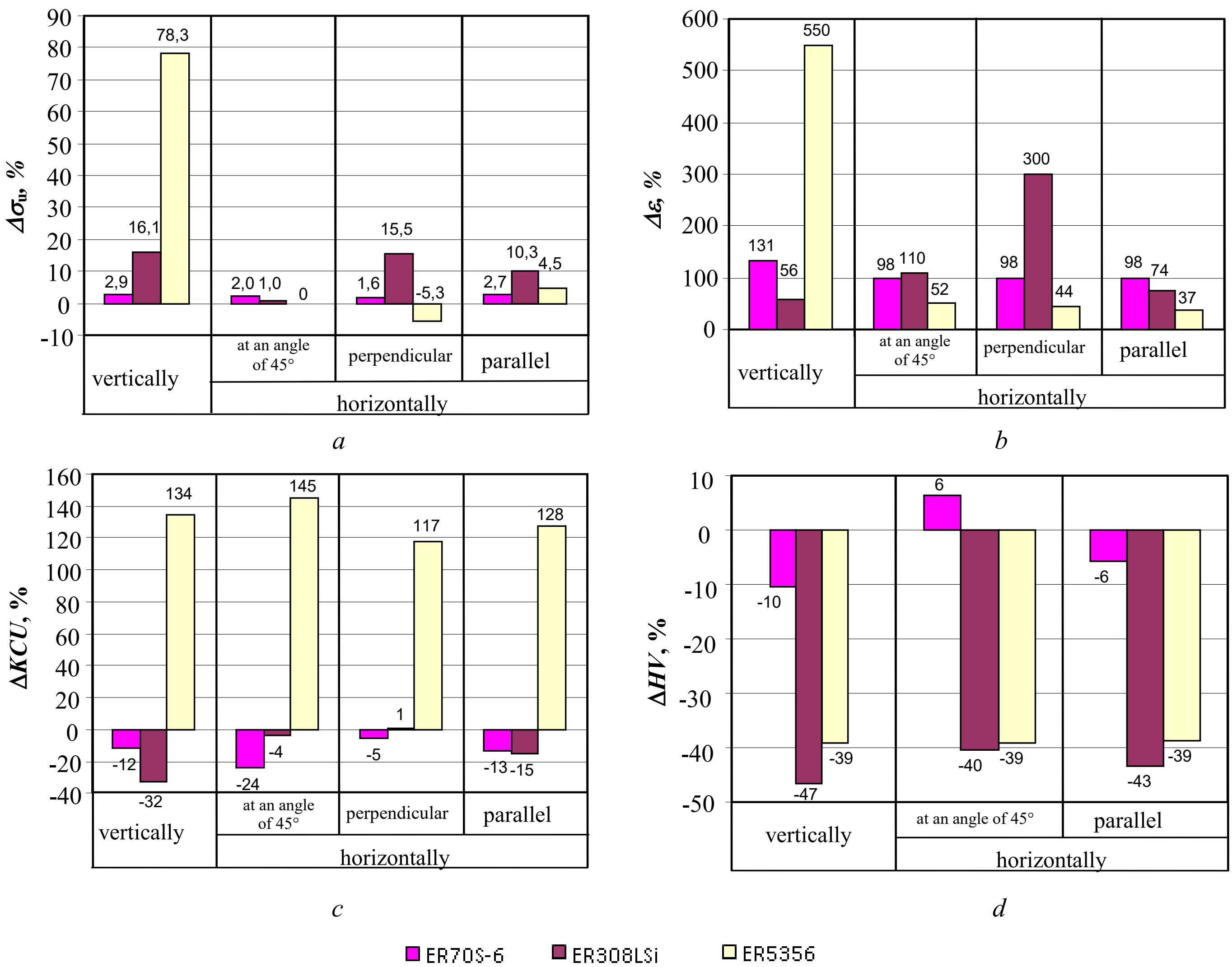

Fig. 4. Relative anisotropy of synthesized samples measured in different directions: tensile strength (*a*), relative elongation (*b*), impact toughness (*c*), and hardness (*d*)

The maximum average hardness value of 212 HV was recorded in the “vertical” direction, the minimum – in the “perpendicular” direction (179 HV), and the average hardness value in the “parallel” direction was 202 HV (Table 2). Therefore, the hardness measured in the “perpendicular” direction is notably lower than in the “parallel” and “vertical” directions (Fig. 5, *a*). The obtained hardness of the synthesized sample is comparable to the hardness of rolled products made from this material in the delivered condition (180–200 HV). The relative hardness anisotropy was 16% (Fig. 4, *d*).

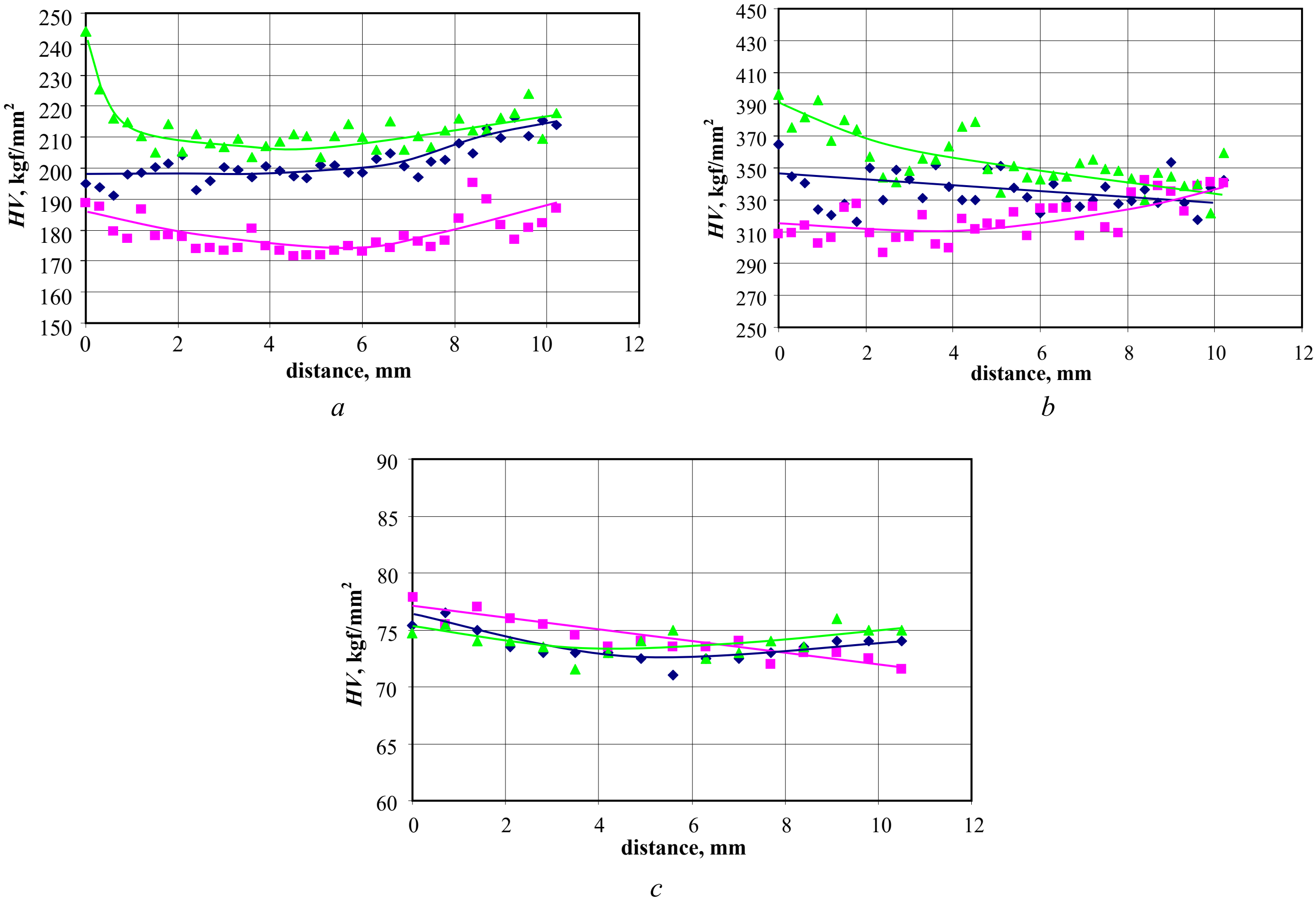

Fig. 5. Hardness of synthesized samples measured in different directions:
0.08 *C*-2 *Mn*-1 *Si* steel (*a*), 0.04 *C*-19 *Cr*-9 *Ni* steel (*b*), 97 AL-3 *Mg* aluminum alloy (*c*)

Analysis of the obtained data on the hardness of all synthesized materials showed that the spread of values in each of the three measurement directions is comparable to that observed when measuring the hardness of alloys produced by casting or rolling.

For steel 0.04 *C*-19 *Cr*-9 *Ni*, the maximum tensile strength of 614 MPa (Table 2) was obtained with the “perpendicular” arrangement of the sample, and the minimum of 534 MPa with the “parallel” one. The obtained values are somewhat inferior to the tensile strength of rolled products made from this material in the delivered condition (610–620 MPa). The tensile strength relative anisotropy was 15.1% (Fig. 4, *a*). The maximum relative elongation of 22% was recorded for the sample with the “parallel” arrangement, and the minimum value of 9% was recorded for the sample with the “horizontal, at an angle of 45°” arrangement. This is significantly inferior to the relative elongation values of rolled products made of this material in the delivered condition (33–36%). The relative anisotropy of the relative elongation was 244% (Fig. 4, *b*).

The maximum impact toughness value was recorded for samples with the “vertical” cutting direction at 177 J/cm² (Table 2), and the minimum – with the “perpendicular” cutting direction (119 J/cm²). This value corresponds to or exceeds the impact toughness of rolled products made from this material in the delivered condition (120 J/cm²). The impact toughness relative anisotropy was 33% (Fig. 4, *c*).

For stainless steel 0.04 *C*-19 *Cr*-9 *Ni*, as well as for steel 0.08 *C*-2 *Mn*-1 *Si*, the highest average hardness value of 355 HV (Table 2) was recorded in the "vertical" direction, the lowest – in the "perpendicular" direction (318 HV), and the average hardness value in the "parallel" direction was 336 HV. Therefore, the hardness measured in the "perpendicular" direction is lower than in the "parallel" direction, and approximately as much lower than in the "vertical" direction (Fig. 5, *b*). The synthesized sample's obtained hardness in all directions significantly exceeds the hardness of rolled products made from this material in the delivered condition (160–180 kgf/mm²). The relative hardness anisotropy was 4% (Fig. 4, *d*).

For the aluminum alloy 97 *Al*-3 *Mg*, the maximum tensile strength of 243 MPa (Table 2) was obtained with the "perpendicular" arrangement of the sample, and the minimum one of 129 MPa – with the "vertical" arrangement. The tensile strength of the samples cut in all horizontal directions, in contrast to the sample cut "vertically", is not inferior to the tensile strength of rolled products made of this material in the delivered condition (200–230 MPa). Specifically due to the "vertical" direction, the tensile strength relative anisotropy was 83.6% (Fig. 4, *a*). The relative elongation with the sample positioned "vertically" is almost 4.5 times lower than that of the samples cut in horizontal directions (2% vs. 8.6–9.4%, respectively). The values of relative elongation in all directions are inferior to the relative elongation of rolled products made from this material in the delivered condition (13%). The relative anisotropy of the relative elongation was 513% (Fig. 4, *b*).

The maximum impact toughness value of 18 J/cm² (Table 2) was recorded for samples with the "perpendicular" cutting direction, the minimum one – with the "horizontal, at an angle of 45°" cutting direction (16 J/cm²). Impact toughness changes insignificantly depending on the location from which the samples are cut out; the relative anisotropy was 28% (Fig. 4, *c*), but is significantly inferior to the impact toughness of rolled products made from this material in the delivered condition (40 J/cm²).

The average hardness value in all directions of measurement was consistent, amounting to 74 HV (Fig. 5, *c*), which exceeds the hardness of rolled products made from this material in the delivered condition by 1.6 times (45 HV). In terms of hardness, the synthesized material can be considered isotropic (Fig. 4, *d*).

The relative anisotropy values of the studied materials in terms of tensile strength, relative elongation, impact toughness, and hardness are presented in Table 3.

Table 3

Relative anisotropy values of the studied materials

Material grade	Relative anisotropy, %			
	of the ultimate tensile strength	of the relative elongation	of the impact toughness	of the hardness
0.08 *C*-2 *Mn*-1 *Si*	1,3	33	21	16
0.04 *C*-19 *Cr*-9 *Ni*	15,1	244	33	4
97 *Al*-3 *Mg*	83,6	513	21	0

It was found that during the synthesis of the studied metallic materials using the *WAAM* method, hardness exhibits the smallest relative anisotropy, while relative elongation shows the largest. The low-carbon steel 0.08 *C*-2 *Mn*-1 *Si* is the most isotropic with respect to all the studied properties. In contrast, the aluminum alloy 97 *Al*-3 *Mg* is the most anisotropic (due to samples cut in the vertical direction). The anisotropy of steel 0.04 *C*-19 *Cr*-9 *Ni* is associated with the low relative elongation values obtained from samples cut in the horizontal plane perpendicular to the torch feed during deposition.

Conclusion

Synthesis of three base materials was carried out using the *WAAM* method: low-carbon alloy steel 0.08 *C*-2 *Mn*-1 *Si*, stainless steel 0.04 *C*-19 *Cr*-9 *Ni*, and aluminum alloy 97 *Al*-3 *Mg*, in order to cover materials with significantly different mechanical properties. Synthesis modes that make it possible to obtain samples with a tensile strength comparable to the tensile strength of rolled products made of the above materials were identified.

The concept of relative anisotropy was introduced as a percentage deviation of the synthesized material properties from the values for the original material (rolled product). This concept is proposed to evaluate both the change in mechanical properties in different directions within the synthesized material and the deviation of these properties from the rolled product.

It was established that for steel 0.08 *C*-2 *Mn*-1 *Si*, the smallest relative anisotropy was observed in ultimate strength (1.3%), and the largest was in relative elongation (33%). Therefore, the material can be considered practically isotropic in terms of strength. The strength of the synthesized steel 0.08 *C*-2 *Mn*-1 *Si* practically corresponds to the strength of rolled steel, but the relative elongation is 2–2.3 times lower.

For 0.04 *C*-19 *Cr*-9 *Ni* steel, the relative anisotropy minimum level was determined by hardness, which was 4%, and the maximum by relative elongation, which was 244%. This allows us to consider the material to be practically isotropic in hardness. At the same time, the hardness of the synthesized steel 0.04 *C*-19 *Cr*-9 *Ni* is close to the hardness of rolled products, and the relative elongation is reduced by 1.5–4 times.

Due to the “vertical” direction, the aluminum alloy 97 *Al*-3 *Mg* demonstrates the greatest anisotropy in tensile strength (83.6%) and in relative elongation (513%). However, anisotropy is absent in hardness, so the obtained material can be considered isotropic in this parameter. Comparison with the initial material shows that hardness is similar to that of rolled products. The tensile strength in the vertical direction is reduced by 1.8 times (in other directions, it is comparable to rolled products), and relative elongation is reduced by 1.4–6.5 times relative to rolled products.

In general, the minimum relative anisotropy is observed in hardness for all materials, which makes hardness the most stable parameter in *WAAM* synthesis. The most significant directions are vertical and horizontal (parallel and perpendicular to the feedstock feed direction during deposition).

References

1. Tomar B., Shiva S., Nath T. A review on wire arc additive manufacturing: Processing parameters, defects, quality improvement and recent advances. *Materials Today Communications*, 2022, vol. 31, p. 103739. DOI: 10.1016/j.mtcomm.2022.103739.

2. Cunningham C.R., Flynn J.M., Shokrani A., Dhokia V., Newman S.T. Invited review article: Strategies and processes for high quality wire arc additive manufacturing. *Additive Manufacturing*, 2018, vol. 22, pp. 672–686. DOI: 10.1016/j.addma.2018.06.020.

3. Hadjipantelis N., Weber B., Buchanan C., Gardner L. Description of anisotropic material response of wire and arc additively manufactured thin-walled stainless steel elements. *Thin-Walled Structures*, 2022, vol. 171, p. 108634. DOI: 10.1016/j.tws.2021.108634.

4. Palmeira Belotti L., van Nuland T.F.W., Geers M.G.D., Hoefnagels J.P.M., van Dommelen J.A.W. On the anisotropy of thick-walled wire arc additively manufactured stainless steel parts. *Materials Science and Engineering: A*, 2023, vol. 863, p. 144538. DOI: 10.1016/j.msea.2022.144538.

5. Williams S.W., Martina F., Addison A.C., Ding J., Pardal G., Colegrove P. Wire + Arc additive manufacturing. *Materials Science and Technology*, 2016, vol. 32 (7), pp. 641–647. DOI: 10.1179/1743284715Y.0000000073.

6. Siddiqui N.A., Muzamil M., Jamil T., Hussain G. Heat sources in wire arc additive manufacturing and their impact on macro-microstructural characteristics and mechanical properties – An overview. *Smart Materials in Manufacturing*, 2025, vol. 3, p. 100059. DOI: 10.1016/j.smmf.2024.100059.

7. Albannai A.I. A brief review on the common defects in wire arc additive manufacturing. *International Journal of Current Science Research and Review*, 2022, vol. 5 (12), pp. 4556–4576. DOI: 10.47191/ijcsrr/V5-i12-19.

8. Sun J., Hensel J., Köhler M., Dilger K. Residual stress in wire and arc additively manufactured aluminum components. *Journal of Manufacturing Processes*, 2021, vol. 65, pp. 97–111. DOI: 10.1016/j.jmapro.2021.02.021.

9. Le V.Th., Mai D.S. Microstructural and mechanical characteristics of 308L stainless steel manufactured by gas metal arc welding-based additive manufacturing. *Materials Letters*, 2020, vol. 271, p. 127791. DOI: 10.1016/j.matlet.2020.127791.

10. Lu X., Zhou Y.F., Xing X.L., Shao L.Y., Yang Q.X., Gao S.Y. Open-source wire and arc additive manufacturing system: Formability, microstructures, and mechanical properties. *The International Journal of Advanced Manufacturing Technology*, 2017, vol. 93 (5–8), pp. 2145–2154. DOI: 10.1007/s00170-017-0636-z.

11. Wahg Y., Chen X., Su Ch. Microstructure and mechanical properties of Inconel 625 fabricated by wire-arc additive manufacturing. *Surface and Coatings Technology*, 2019, vol. 374, pp. 116–123. DOI: 10.1016/j.surfcoat.2019.05.079.

12. Vlasov I.V., Gordienko A.I., Kuznetsova A.E., Semenchuk V.M. Structure and mechanical properties anisotropy of a steel product manufactured by layer-by-layer electric arc wire 3D printing. *Izvestiya. Ferrous Metallurgy*, 2023, vol. 66 (6), pp. 709–717. DOI: 10.17073/0368-0797-2023-6-709-717.

13. Nagasai B., Malarvizhi S., Balasubramanian V. Mechanical properties of wire arc additive manufactured carbon steel cylindrical component made by gas metal arc welding process. *Journal of the Mechanical Behavior of Materials*, 2021, vol. 30 (1), pp. 188–198. DOI: 10.1515/jmbm-2021-0019.

14. Yang X., Liu J., Wang Zh., Lin X., Liu F., Huang W., Liang E. Microstructure and mechanical properties of wire and arc additive manufactured AZ31 magnesium alloy using cold metal transfer process. *Materials Science and Engineering: A*, 2020, vol. 774, p. 138942. DOI: 10.1016/j.msea.2020.138942.

15. Rosli N.A., Alkahari M.R., Abdollah M.F. bin, Maidin Sh., Ramli F.R., Herawan S.G. Review on effect of heat input for wire arc additive manufacturing process. *Journal of Materials Research and Technology*, 2021, vol. 11, pp. 2127–2145. DOI: 10.1016/j.jmrt.2021.02.002.

16. Selvi S., Vishvaksenan A., Rajasekar E. Cold metal transfer (CMT) technology – An overview. *Defence Technology*, 2018, vol. 14 (1), pp. 28–44. DOI: 10.1016/j.dt.2017.08.002.

17. Nguyen Q.L. *Tool path planning for wire-arc additive manufacturing processes*. Thesis for: Doctoral. BTU Cottbus – Senftenberg, 2022. DOI: 10.26127/BTUOpen-5982.

18. Rajput G.S., Gor M., Soni H., Badheka V., Sahlot P. Effect of deposition strategies on mechanical strength of wire arc additively manufactured Inconel 625. *Materials Today: Proceedings*, 2022, vol. 62 (13), pp. 7324–7328. DOI: 10.1016/j.matpr.2022.05.164.

19. Andreacola F.R., Capasso I., Langella A., Brando G. 3D-printed metals: Process parameters effects on mechanical properties of 17-4 P H stainless steel. *Heliyon*, 2023, vol. 9 (7), p. e17698. DOI: 10.1016/j.heliyon.2023.e17698.

20. Kirichek A.V., Fedonin O.N., Khandozhko A.V., Zhirkov A.A., Soloviyov D.L., Barinov S.V. Gibridnye tekhnologii i oborudovanie additivnogo sinteza izdelii [Hybrid technologies and technical equipment for additive synthesis of products]. *Naukoemkie tekhnologii v mashinostroenii = Science Intensive Technologies in Mechanical Engineering*, 2022, no. 8 (134), pp. 31–38. DOI: 10.30987/2223-4608-2022-8-31-38.

21. Li S., Lin Z., Kirichek A.V., Nagorkin M.N., Novikov M.A. Vliyanie tekhnologicheskikh faktorov na protsessy formirovaniya parametrov kachestva izdelii, izgotavlivaemykh WAAM-metodom na osnove dugovoi svarki v zashchitnykh gazakh [Technology factors effect on the quality parameters of products manufactured by the WAAM-technique based on GMAW (gas-metal-arc-welding)]. *Naukoemkie tekhnologii v mashinostroenii = Science Intensive Technologies in Mechanical Engineering*, 2025, no. 5 (167), pp. 3–14. DOI: 10.30987/2223-4608-2025-5-3-14.

Conflicts of Interest

The authors declare no conflict of interest.