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ADJAMSKIY, S.[1] (https://orcid.org/0000-0002-6095-8646),
KONONENKO, G.[1,2] (https://orcid.org/0000-0001-7446-4105),
PODOLSKYI, R.[1,2] (https://orcid.org/0000-0002-0288-0641),
and BADUK, S.[1] (https://orcid.org/0000-0002-1074-3057),

[1] Additive Laser Technology of Ukraine, LLC,
31b, Serhiy Podolinsky St., Dnipro, 49000, Ukraine,
+380 98 720 6127, info@alt-print.com
[2] Iron and Steel Institute of Z. I. Nekrasov, the National Academy of Sciences of Ukraine,
1, Ak. Starodubov Sq., Dnipro, 49107, Ukraine,
+ 380 56 790 0514, okc.testcenter@ukr.net

STUDYING THE INFLUENCE OF ORIENTATION AND LAYER THICKNESS ON THE PHYSICO-MECHANICAL PROPERTIES OF Co-Cr-Mo ALLOY MANUFACTURED BY THE SLM METHOD

Introduction. *The additive manufacturing technologies have recently become more widespread in modern production, as they allow the quick and efficient manufacture of products with a unique geometry.*

Problem Statement. *For the production of parts, it is necessary to use rational technological parameters that depend on the characteristics of the material and equipment for selective laser melting (SLM). Among the factors affecting the mechanical properties there are the sample orientation in the working chamberand the thickness of the working layer.*

Purpose. *The purpose of this research is to study the effect of sample orientation in the direction of the X, Y, Z axes and layer thickness (40 and 20 μm) on the physical and mechanical properties of the Co-Cr-Mo alloy fabricated by the selective laser melting method.*

Material and Methods. *All prototypes are made of Co-Cr-Mo alloy powder with a particle size of 10–45 μm. The samples are printed with layer thicknesses of 20 and 40 μm, with the use of an Alfa-150 3D printer manufactured by ALT Ukraine LLC. The samples for tensile tests are placed on the platform in horizontal (X and Y axes) and vertical (Z axis) positions. The tests to determine the mechanical properties have been carried out in accordance with ISO 6892:2019, on a PHYWE testing machine. The thermal expansion coefficient has been determined with the use of a DIL.A.802 dilatometer.*

Results. *The dependence of the metaldensity at a constant thickness of the deposited layer of 40 and 20 μm and a distance between tracks of 0.1—0.12 mm has been established, and the rational conditionsfor manufacturing samples for tensile tests have been chosen.*

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Conclusions. *It has been established that a decrease in the intertrack distance contributes to the achievement of a density of 99.99% and an increase in the area of the rational printing conditions. It has been shown that the samples printed with different thicknesses of the working layer have different mechanical properties. When comparing samples made at different layer thicknesses and placed in the same direction, we have found that the temporary resistanceis the lowest for the vertical samples as compared with the horizontal ones in the X and Y directions.*

Keywords: cobalt-chromium alloy, Co-Cr-Mo, density, microstructure, mechanical properties, orientation, coefficient of thermal expansion.

Recently, additive manufacturing technologies have become more and more widespread in modern production, as they allow the quick and qualitative creation of products with a unique geometry, as well as the expansion of the number of materials that can be used.

The research deals with selective laser melting (SLM) that is an iterative process consisting of the three main stages: (1) the application of a powder layer having a thickness of 20 to 50 μm on the construction platform; (2) the local melting of the powder layer by a laser source based on previously imported 3D-CAD data; and (3) the lowering of the construction platform and the repetition from step (1). The powder is usually applied with a polymer or rubber scraper.

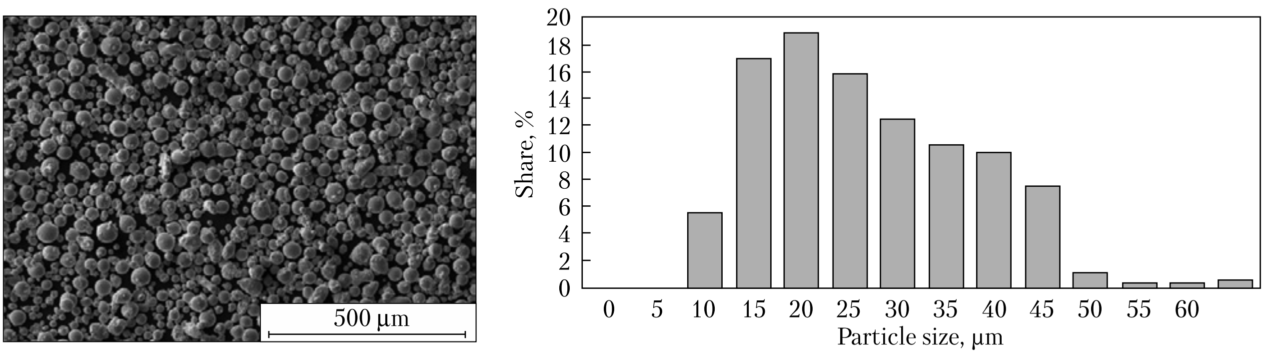
In the last two years, the authors of research [1—3] mainly focused on process control, including the influence of various parameters on the process stability, the resulting microstructure, and the material properties [4—6].

For the production of parts, rational and material-dependent technological parameters for the corresponding SLM device,as provided by its manufacturer, are often used. The physico-mechanical properties of samples made with the use of-SLM have been analyzed in the course of many studies [7—8]. The authors of these studies always use their own developed process parameters depending on equipment, therefore the technological parameters cannot provide the same level of physical and mechanical properties if applied in industrial process of other manufacturers.

Studies [7, 9] have given an understanding of the influence of many factors,such as powder layer density, powder application processes, heat flow, and temperature distribution, which arepresent in SLM processes. In addition, the formation of defects and microstructure during these processes has been simulated in [7, 12—14].

The purpose of the research is to study the influence of the sampleorientation in the *X, Y, Z* axes and the layer thickness (40 μm and 20 μm) on the physical and mechanical properties of the cobalt-chromium alloy (Co-Cr-Mo) produced by the SLM method.

All test samples are made of Co-Cr-Mo cobalt-chromium alloy powder with the following che-



a *b*

Fig. 1. Particles of original Co-Cr-Mo material enlarged 200 times (*a*) and the granulometric analysis results (*b*)

mical composition, in % wt.: Cr = 17.79; Ni = 12.63; Mo = 2.35; Mn = 0.78; Si = 0.64; C = 0.016 [1—3]. The powder bulk density is 4880 kg/m^3. To determine the shape and size of the particles, the powder is studied with the use of a SEM-106 scanning electron microscope (Fig. 1, *a*). Figure 1, *b* shows the results of the granulometric analysis made with the help of specialized software *Image J* by the method of secants. It has been established that the size of the particles ranges from 10 to 45 μm. All test samples are printed by an *Alfa-150* 3D printer manufactured by *ALT Ukraine* LLC [15, 17].

The material for studies of the effect of printing conditions and layer thickness (20 and 40 μm) on the metal density are10 × 10 × 5 mm samples.

To determine the influence of the layer thickness and the shift of the position in the chamber on the mechanical properties of the metal, the samples for the tensile tests are made according to the tested rational printing conditions established during the study of the 10 × 10 × 5 mm samples: power is 195 W, scanning speed is 1150 mm/s, distance between tracks is 0.1 mm. The samples are placed on the platform in horizontal (along the *X* and *Y* axis) and vertical (along the *Z* axis) positions (Fig. 2). Before the test, all samples aremachined by a lathe [3]. The tests to determine the mechanical properties [15—17] have been made in accordance with ISO 6892, on PHYWE testing machine.

The 50 × Ø5 mm samples made by the SLM technology are tested to determine the coefficient of thermal expansion (CTE) with the use of a dilatometer DIL.A.802.

In order to work out the rational conditions of the printing process, samples are made of Co-Cr-Mo cobalt-chromium alloy powder, with the use of theSLM technology,in accordance with the experimental conditions (the power varrieswithin the range of 150—195 W, the scanning speed ramges from 800—1200 mm/s, the distance between tracks is within 0.1—0.12 mm).The thickness of the layer is 40 μm and 20 μm (see Tables 1, 2, respectively). The criterion for choosing the rational conditions of making the test samples is

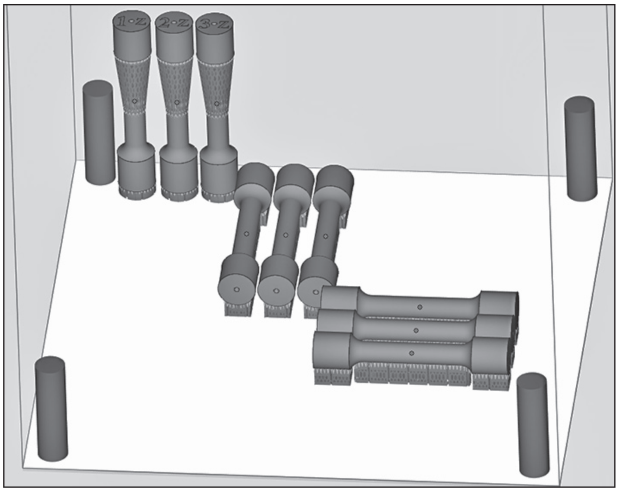


Fig. 2. Location of the samples on the platform

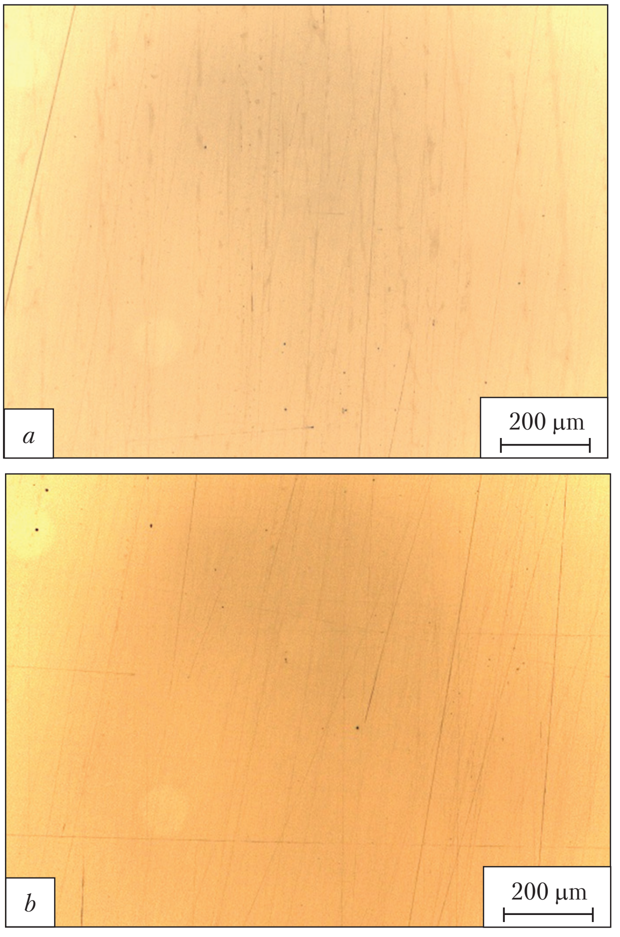


Fig. 3. Microstructure of the samples made at a layer thickness of 40 μm (*a* — sample No. 7; *b* — sample No. 31)

Table 1. **Experimental Conditions of SLM Technology for thePrinting from Co-Cr-Mo Cobalt-Chromium Alloy Powder with a 40 μm Thick Layer**

Sample number	Power, W	Speed, mm/s	Distance between tracks, mm
1	150	800	0.1
2	150	800	0.11
3	150	800	0.12
4	170	800	0.1
5	170	800	0.11
6	170	800	0.12
7	195	800	0.1
8	195	800	0.11
9	195	800	0.12
10	150	900	0.1
11	150	900	0.11
12	150	900	0.12
13	170	900	0.1
14	170	900	0.11
15	170	900	0.12
16	195	900	0.1
17	195	900	0.11
18	195	900	0.12
19	170	1000	0.1
20	170	1000	0.11
21	170	1000	0.12
22	195	1000	0.1
23	195	1000	0.11
24	195	1000	0.12
25	195	1050	0.1
26	195	1050	0.11
27	195	1050	0.12
28	195	1100	0.1
29	195	1100	0.11
30	195	1100	0.12
31	195	1150	0.1
32	195	1150	0.11
33	195	1150	0.12
34	195	1200	0.1
35	195	1200	0.11
36	195	1200	0.12

Table 2. **Experimental Conditions of the SLM Technology for the Printing from Co-Cr-Mo Cobalt-Chromium Alloy Powder with a 20 μm Thick Layer**

Sample number	Power, W	Speed, mm/s	Distance between tracks, mm
37	130	800	0.1
38	130	800	0.11
39	130	800	0.12
40	150	800	0.1
41	150	800	0.11
42	150	800	0.12
43	130	900	0.1
44	130	900	0.11
45	130	900	0.12
46	150	900	0.1
47	150	900	0.11
48	150	900	0.12
49	130	1000	0.1
50	130	1000	0.11
51	130	1000	0.12
52	150	1000	0.1
53	150	1000	0.11
54	150	1000	0.12
55	170	1000	0.1
56	170	1000	0.11
57	170	1000	0.12
58	150	1100	0.1
59	150	1100	0.11
60	150	1100	0.12
61	170	1100	0.1
62	170	1100	0.11
63	170	1100	0.12
64	195	1100	0.1
65	195	1100	0.11
66	195	1100	0.12
67	170	1200	0.1
68	170	1200	0.11
69	170	1200	0.12
70	195	1200	0.1
71	195	1200	0.11
72	195	1200	0.12

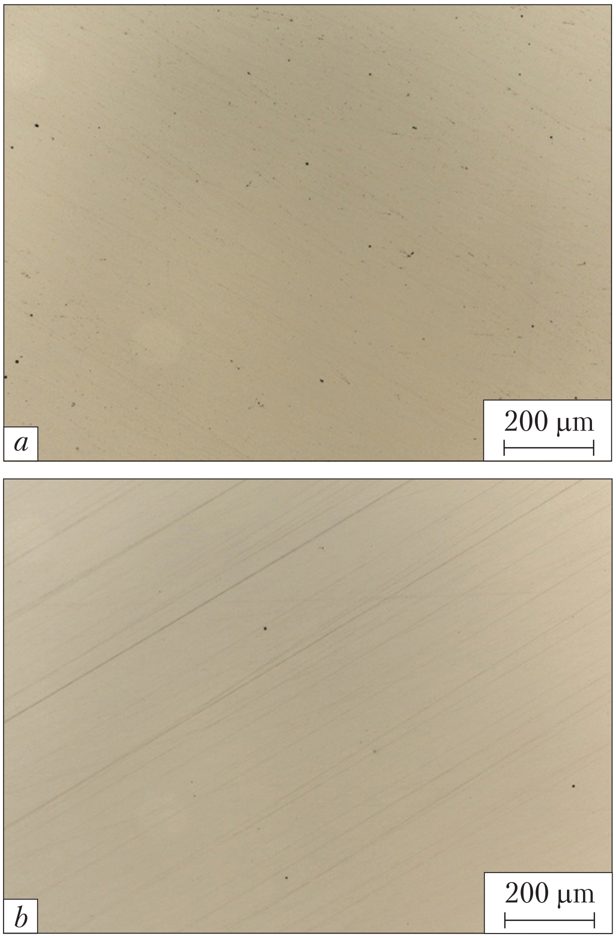


Fig. 4. Microstructure of the samples made at a layer thickness of 20 μm (*a* — sample No. 46; *b* — sample No. 71)

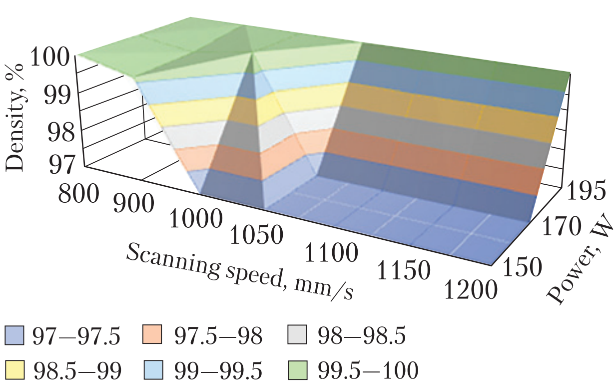


Fig. 5. Density of the samples printed with a layer thickness of 40 μm and a distance between tracks of 0.1 mm

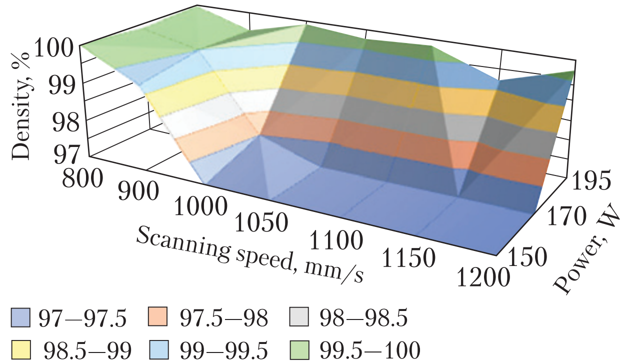


Fig. 6. Density of the samples printed with a layer thickness of 40 μm and a distance between tracks of 0.11 mm

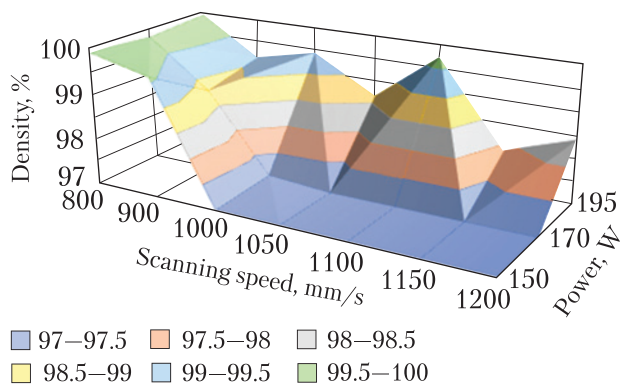


Fig. 7. Density of the samples printed with a layer thickness of 40 μm and a distance between tracks of 0.12 mm

the actual density of metal, which is determined based on the results of the metallographic assessment of porosity by the percentage of the area occupied by pores (Figs. 3 and 4).

As a result of the studies, the dependence of the metal density at a constant thickness of the applied layer of 40 (Fig. 5–7) and 20 μm (Fig. 8–10) and a constant distance between the tracks of 0.1 mm (Fig. 5, 8), 0.11 mm (Fig. 6, 9), and 0.12 mm (Fig. 7, 10) has been established.

According to the results of the studies of the effect of the printing conditions at 40 μm on the metal density, the rational conditionshave been established: the power is 195 W, the scanning speed is 800 mm/s; 1050 mm/s; and 1100 mm/s. It should be noted that as the distance between the tracks increases, the area on the graph (Fig. 6)

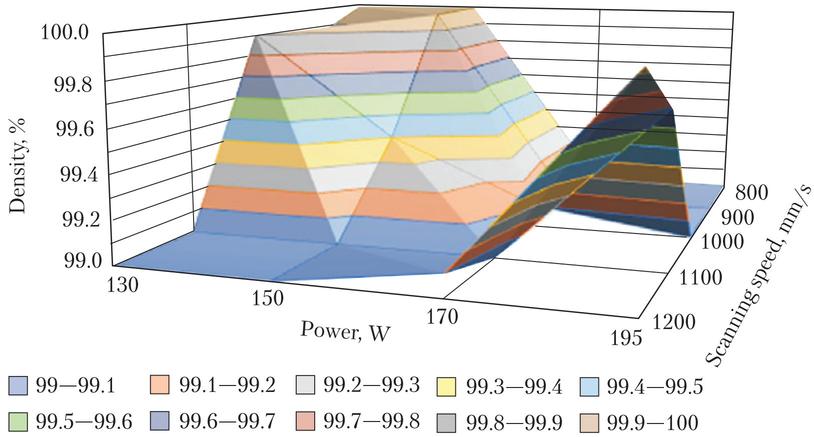


Fig. 8. Density of the samples printed with a layer thickness of 20 μm and a distance between tracks of 0.1 mm

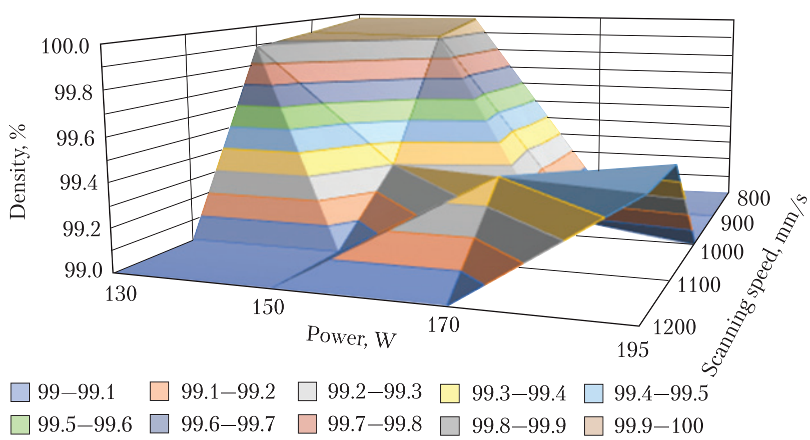


Fig. 9. Density of the samples printed with a layer thickness of 20 μm and a distance between tracks of 0.11 mm

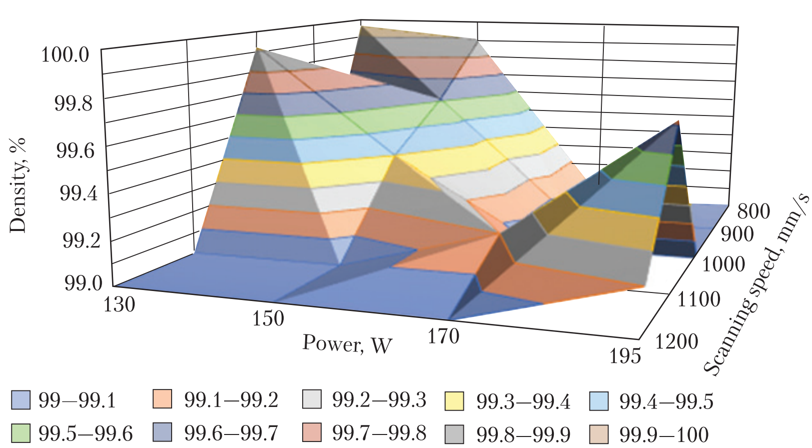


Fig. 10. Density of the samples printed with a layer thickness of 20 μm and a distance between tracks of 0.12 mm

with a high density (99.90—99.99%) of the samples decreases by 13% for a distance of 0.11 mm and by 32% for a distance of 0.12 mm (Fig. 7), as compared withthe samples made with a distance between tracks of 0.1 mm (Fig. 5). It has been shown that as the distance between the tracks increases, the area having a density of at least 99.99% decreases 3.6 and 7.3 times (Figs. 6 and 7, respectively) in comparison with the samples made with a distance between tracks of 0.1 mm (Fig. 5).

According to the results of the studies of the effect of printing conditions at 20 μm on the metal density, the rational process conditions have been established as follows: the power is 130—150 W, the scanning speed is 800—1000 mm/s. It should be noted that as the power (170—195 W) and the scanning speed (1100—1200 mm/s) increase, so does the density. As the distance between the tracks increases, the area on the graph (Fig. 9) with a high density (99.90—99.99%) of the samples decreases by 7% for a distance of 0.11 mm and by 13.2% for a distance of 0.12 mm (Fig. 10), in comparison with the samples made with a distance between tracks of 0.1 mm (Fig. 8). It has been shown that as the distance between the tracks increases, the areahaving a density of at least 99.99% decreases 2 and 3.8 times (Figs. 9 and 10, respectively) as compared with the samples made with a distance between tracks of 0.1 mm (Fig. 8).

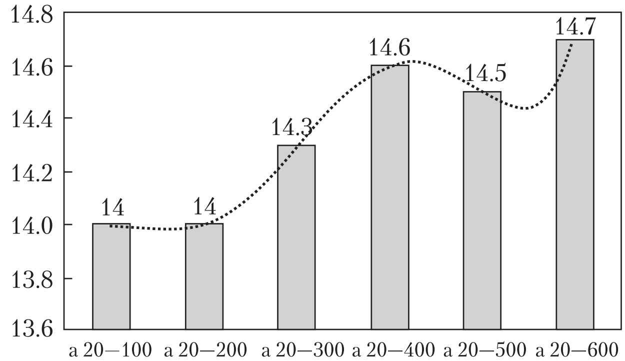


Fig. 11. Coefficient of thermal expansion

Given the obtained results, we made samples for tensile tests in the same mode (power is 195 W, scanning speed is 1150 mm/s, distance between tracks is 0.1 mm) in order to determine the effect

Table 3. **Mechanical Properties of the Samples Made with 40 μm and 20 μm Thick Layers and Placed in the Direction of the *X, Y, Z* Axes**

Thickness	40 μm						20 μm					
Marking	$\sigma_в$		δ_5		Ψ		$\sigma_в$		δ_5		Ψ	
	MPa	$\Delta^{x,y,z}$*	%	$\Delta^{x,y,z}$*	%	$\Delta^{x,y,z}$*	MPa	$\Delta^{x,y,z}$*	%	$\Delta^{x,y,z}$*	%	$\Delta^{x,y,z}$*
1*x*	1209	+0.69	7.3	+37.73	14.3	+26.54	1291	+0.20	7.5	+30.24	10.9	+19.38
2*x*	1213	+1.03	4.6	–13.20	14.3	+26.54	1286	–0.17	5.0	–13.19	7.9	–13.47
3*x*	1180	–1.71	4.2	–20.75	5.5	–51.32	1288	–0.02	4.8	–16.66	8.6	–5.8
Mean *x*	**1200.6**	**0**	**5.3**	**0**	**11.3**	0	**1288.3**	**0**	**5.76**	**0**	**9.13**	**0**
1*y*	1135	–1.56	6.2	–20.51	4.3	–53.76	1251	–0.76	6.5	–10.95	7.8	0
2*y*	1150	–0.26	10.5	+34.61	9.9	+6.45	1263	+0.19	8.7	+19.17	7.8	0
3*y*	1174	+1.82	6.7	–14.10	13.9	+49.46	1268	+0.58	6.7	–8.21	7.8	0
Mean *y*	**1153**	**0**	**7.8**	**0**	**9.3**	**0**	**1260.6**	**0**	**7.3**	**0**	**7.8**	**0**
1*z*	1045	–1.41	2.2	–69.44	5.5	–9.83	1157	–0.19	1.8	–74.13	17.9	+23.78
2*z*	1084	+2.24	9.2	+17.94	6.7	+9.83	1162	+0.23	8.7	+25	10.1	–30.15
3*z*	1053	–0.66	10.4	+44.4	6.3	+3.27	1159	–0.02	10.4	+49.42	15.4	+6.50
Mean *z*	**1060**	**0**	**7.2**	**0**	**6.1**	**0**	**1159.3**	**0**	**6.96**	**0**	**14.46**	**0**

Note: * $\Delta^{x,y,z}$ is deviation (%) from the mean value in direction *X, Y, Z*.

of layer thickness and sample orientation on the mechanical properties (temporal resistance, relative elongation, relative narrowing). The results of these studies are presented in Table 3.

When comparing the relative elongation values, we have established that the samples made at 40 μm have a plasticity by 2—5% higher than the samples made at 20 μm. At the same time, the strength characteristics of the samples made with a layer thickness of 20 μm are higher by ~10%. The vertical samples made with a layer thickness of 20 μm have a temporary resistance by 8.5% more than those made with a layer thickness of 40 μm. This characteristic has the lowest values for the vertical samples as compared with the horizontal ones in the *X* and *Y* directions. When comparing the samples made with different layer thicknesses and in the same direction (*X* axis), we have been established that the temporary resistance differs byabout 6%. The samples made with a layer thickness of 20 μm in the direction of the *Y* axis have a temporary resistance by 8.5% higher than the same oriented samples with a layer thickness of 40 μm.

Cobalt-chromium alloy products are often used in the dental industry, namely for dental crowns on which porcelain or metal ceramics are applied by sintering. In this regard, the coefficient of thermal expansion (CTE) is an important characteristic.

In the research, changes in the geometric dimensions of the sample during the heating up to a temperature of 600 °C have been studied (Fig. 11). It has been established that the CTE remains constant(14 μm/m/K) up to a temperature of 200 °C. As the temperature increases (300—600 °C), so does the CTE. It has been shown that in the temperature range of 400—600 °C, the coefficient is 14.6 μm/m/K ± 0.1 μm/m/K.

Thus, the change in this coefficient at a temperature from 20 to 600 °C is 0.7 μm/m/K for the studied Co-Cr-Mo alloy produced by the SLM method, while for dental porcelain and metal ceramics used in the production of dental prostheses, theCTE is 2.0—2.5 μm/m/K and 2.5—3.1 μm/m/K, respectively. That is, the CTE of the Co-Cr-Mo alloy produced by the SLM method is much smaller than that of the coating. Thus, on the basis of this study, it has been proved that at a high temperature, the metal base of the crown made of the studied alloy does not significantly change its geometry during the subsequent sintering of porcelain and metal ceramics. That is, the material meets the necessary condition to prevent chipping of porcelain and metal ceramics in the final product, and this alloy can be used in the medical field (dentistry), including forcreating a coating of products with porcelain and metalceramics by the sintering method.

CONCLUSIONS

1. From the analysis of the influence of the experimental conditions, it has been established that as the distance (0.11 and 0.12 mm) between the tracks increases, at a constant layer thickness, the number of pores increases by 13% and by 32% (40 μm) and by 7% and by 13.2% (20 μm), respectively, as compared with a distance of 0.1 mm.

2. The dependence of the density change on the process parameters at a constant distance between the tracks of 0.1 mm,0.11 mm, and 0.12 mm and a layer thicknesses of 40 μm and 20 μm has been established. It has been shown that as the distance between the tracks increases, the area having a density of at least 99.99% decreases,as compared with the samples made with a distance between tracks of 0.1 mm.

3. The rational printing conditions with a layer thickness of 20 μm have been established: for a distance between tracks of 0.1 mm, the power is 130—150 W, the scanning speed is 800—1000 mm/s. For a layer thickness of 40 μm: the power is 195 W, the scanning speed is 800 mm/s and 1000—1100 mm/s.

4. The influence of the layer thickness and the position of the samples relative to the chamber axes in the course of their making on the mechanical properties has been determined. It has been shown that in the case of a working layer thickness of 20 μm the temporary resistance is higher

by 6—9% and plasticity is higher by about 10%, as compared with those for a thickness of 40 μm. The temporary resistance is the lowest in the case of the vertical samples (direction of the *Z* axis) as compared with the horizontal ones (in the *X* and *Y* directions).

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С. В. Аджамський[1] (https://orcid.org/0000-0002-6095-8646),
Г. А. Кононенко[1, 2] (https://orcid.org/0000-0001-7446-4105),
Р. В. Подольський[1, 2] (https://orcid.org/0000-0002-0288-0641),
С. І. Бадюк[1] (https://orcid.org/0000-0002-1074-3057)

[1] LLC «Additive Laser Technology of Ukraine»,
вул. СергіяПодолинського, 31б, Дніпро, 49000, Україна,
+380 98 720 6127, info@alt-print.com,
[2] Інститут чорної металургії ім. З. І. Некрасова Національної академії наук України,
пл. акад. Стародубова К.Ф., 1, Дніпро, 49107, Україна,
+380 56 790 0514, okc.testcenter@ukr.net

ДОСЛІДЖЕННЯ ВПЛИВУ ОРІЄНТУВАННЯ ТА ТОВЩИНИ ШАРУ ДРУКУ НА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ СПЛАВУ Co-Cr-Mo, ВИГОТОВЛЕНОГО МЕТОДОМ СЛП

Вступ. Технології адитивного виробництва останнім часом набувають все більшого поширення у сучасному виробництві, оскільки дозволяють швидко та якісно створювати вироби з унікальною геометрією.

Проблематика. Для виробництва деталей необхідно використовувати раціональні технологічні параметри, які залежать від характеристик матеріалу та обладнання селективного лазерного плавлення (СЛП). Серед факторів, що впливають на механічні властивості, є такі як орієнтація в робочій камері побудови та товщина робочого шару.

Мета. Дослідження впливу орієнтування зразків в напрямку осей *X*, *Y*, *Z* та товщини шару (40 та 20 мкм) на фізико-механічні властивості сплаву Co-Cr-Mo виготовлених методом селективного лазерного плавлення.

Матеріали й методи. Всі дослідні зразки було виготовлено з порошку Co-Cr-Mo сплаву з розміром частинок від 10 до 45 мкм. Друк зразків при товщинах шару 20 та 40 мкм проводився на 3*D* принтері *Alfa*-150 виробництва компанії ТОВ «АЛТ Україна». Розташовувалися зразки для випробуваньна розтягування на платформі в горизонтальному (осі *X* та *Y*) і вертикальному положенні (вісь *Z*). Випробування для визначення механічних властивостей проводили відповідно до ISO 6892:2019 на випробувальній машині «*PHYWE*». Коефіцієнт температурного розширення визначали за допомогою дилатометру *DIL.A*.802.

Результати. Встановлено залежність щільності металу при постійній товщині нанесеного шару 40 та 20 мкм та відстані між треками 0,1—0,12 мм та обрано раціональні режими для виготовлення зразків на розтягування.

Висновки. З'ясовано, що зменшення міжтрекової відстані сприяє досягненню щільності 99,99% та збільшенню області раціональних режимів друку. Показано, що зразки, надруковані при різній товщині робочого шару, мають різні значення механічних властивостей. При порівнянні зразків, побудованих при різній товщині шару та в однаковому напрямку, з'ясовано, що значення тимчасового опор має найнижчі значення для вертикальних зразків порівняно з горизонтальними в напрямах *X* та *Y*.

Ключові слова: кобальт-хромовий сплав, Co-Cr-Mo, щільність, мікроструктура, механічні властивості, орієнтація, коефіцієнт температурного розширення.