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Fatigue properties of AlSi10Mg obtained by additive manufacturing: Effect of post treatment

Additive manufacturing and, in particular, 3D-printing of metals and alloys has been actively developing in recent years. More and more complex parts can be produced with the involvement of more alloys. One of the most common and universal methods of 3D-printing is a selective laser melting (SLM). In turn, one of the most common and widely used alloys for SLM is the AlSi10Mg. It belongs to the class of cast alloys and is widely used in many industries due to its high specific strength, corrosion resistance, low coefficient of thermal expansion and low cost. For most additively manufactured metal parts, an important problem that needs to be solved is the provision of sufficient fatigue strength, which is associated with a relatively high defectivity of the product surfaces.

The article is devoted to the review of methods of postprocessing of SLM-printed parts, made of AlSi10Mg alloy, which can increase their fatigue strength. It is noted that, in addition to the quality of the surface, the main reasons for the alloys reduced tensile strength include residual stresses caused by point overheating and cooling of metal microvolumes during the parts formation.

Heat treatment, in particular – low-temperature annealing for stress relief at 250 °C with subsequent cooling in water, leads to an increase in fatigue strength by 18 %, and T6 hardening according increases the load limit by 20–40 MPa. This is explained by the silicon particles spheroidization.

Hot isostatic pressing reduces the porosity of samples, as well as residual stress and homogenizes the structure, but also leads to a decrease in microhardness, yield strength, and fatigue strength.

Sandblasting surface treatment by using a mixture of aluminum, silicon and zirconium oxides helps to reduce surface roughness by one and a half to two times, almost completely removes surface porosity and creates compressive stresses, which in turn increases fatigue strength.

The perspective of ultrasonic surface treatment of 3D-products was also noted. It has a similar effect to sandblasting surface treatment, but it seems to be more effective.

Ключові слова: 3D-printing; SLM, AlSi10Mg; fatigue strength; surface treatment; heat treatment.

Introduction. Since the 1980s, the innovative Additive Manufacturing (AM), commonly referred to as three-dimensional (3D) printing, is becoming the effective technology in the various industries such as aerospace, automotive, and biomedical, thanks of the such benefits: suitability for rapid manufacturing of complex structures,

adaptability for personalized customization, without the need of machining operations, and applicability for crafting items with high added value. Specifically, in the aircraft industry AM is receiving more and more attention to produce parts with complex geometry, limited mass loss, and also leads to important weight reduction [1-3].

Metal additive manufacturing and specifically Laser Powder Bed Fusion, including Selective laser melting (SLM) is considered as one of the most innovative manufacturing technology and has rapidly gained interest in industry because it allows to produce the near-net-shape components characterized by complex geometry [4-7].

SLM procedure allows for the direct printing of the metal component directly from the 3D computer-aided design (CAD) by fusing fine metal powder in layers by the high-power laser beam quickly and precisely (Fig. 1). The powders for the next layer are covered on the melted layer, and the laser is again scanned according to the next sliced data. This sequence continues until the near-net-shape of the products is formed automatically. SLM has the ability to fully melt metal into the solid 3D-structure [8].

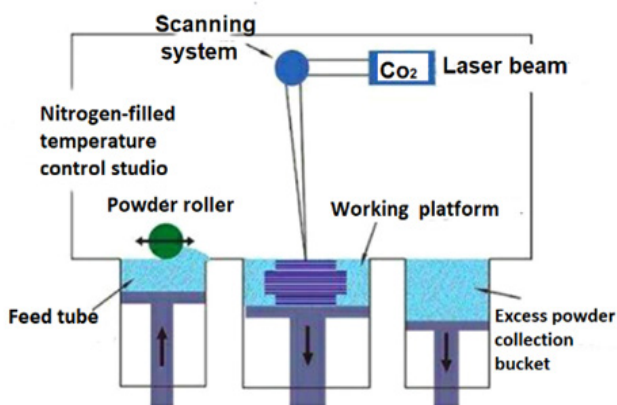


Fig. 1. The SLM process principal scheme [8]

In recent years, considering the advantages of SLM technology and the characteristics of AISi10Mg alloys, these alloys have become important candidates for additive manufacturing. 3D-printing with AISi10Mg allows for the creation of complex geometries that would be difficult or impossible to produce using traditional manufacturing methods. Among aluminium alloys, AISi10Mg stands out as one of the most extensively researched aluminum alloys in SLM [9-13].

AISi10Mg alloy is the representative of the cast aluminium alloys and is extensively used in the aerospace and automotive industries for lightweight applications because of its high strength-to-weight ratio, lightweight, low density, good corrosion resistance properties, low coefficient of thermal expansion, excellent wear resistance, high specific strength compared to other materials, excellent castability, and weldability. This hypoeutectic alloy is near the eutectic typical chemical composition: (wt.%): Mg – 0.2-0.45; Si – 9-11; Fe < 0.55; Cu < 0.05; Mn < 0.45; Ni < 0.05; Zn < 0.1; Pb < 0.05; Sn < 0.05; Ti < 0.15; Al – bal. [14]. The specific material properties are for this alloy: Elastic modulus $E = 75$ GPa, Yield Stress $\sigma_T = 275$ MPa and density $\rho = 2.7$ g/cm³ [15; 16].

Fatigue is one of the most important mechanical characteristics of the engineering materials since the cyclic stress may induce small deformations and damage accumulation, that reduces the fatigue life of a component

and thereby cause a catastrophic failure. In particular, in the aeronautical context, the realization of the parts requires the understanding of the fatigue behavior in relation to integrity of the metal material. It is estimated that about 90 % of the engineering failures are related to fatigue fracture. It usually breaks suddenly without any warning and leads to catastrophic accidents [17-21]. Therefore, it is necessary to perform in-depth studies the fatigue behavior especially for parts manufactured using AM technologies. In recent years, the fatigue life prediction for AISi10Mg samples produced by SLM, including the post-treated ones, has been extensively studied by many researchers. The main results of such works are presented below.

Let us note the main structural and technological factors influencing the fatigue characteristics of the SLM manufactured and post-treated AISi10Mg alloy samples: residual stress, surface roughness and integrity, structure/phase morphologies as well as post-production heat treatment and surface finishing.

Residual stresses (RS). RS in the SLMed samples are caused by the high spatial temperature gradients. This is because, when the entirely new alloy layer is melted simultaneously and deposited, of the new layer has the higher temperature than the underlying layer which is cooling uniformly in the 3D-printing direction [22; 23]. It is well known that tensile RS is detrimental to the fatigue strength of both conventional and AM materials [24] because it alters the mean stress and load ratio during cyclical loading and has a significant influence on the crack propagation rate and leads to anisotropic crack growth behavior [25-27]. The relief of RS and their subsequent stabilization were the main mechanisms responsible for improving the fatigue strength. Compressive residual stresses induced by surface modification and finishing can be also beneficial [28; 29]. One of the effective ways to reduce RS is the post-heat treatment.

Post-heat treatment. Several conventional heat treatments have been explored, including the investigation of the conventional T6 procedure [30]. This study shows the importance of optimizing the applied heat treatment for AISi10Mg components produced using SLM. Thus, an optimized heat treatment with temperatures below the threshold of Si precipitation was developed in order to improve the fatigue strength of the material. That post processing heat treatment was enough to relax the SLM induced tensile stress.

The variation in the cyclic stress characteristics with the fatigue life and microstructural features, such as modulation in the cellular structure and Si particles with the influence of different types of the heat treatment, was studied. Surface deformation and finishing methods, such as shot peening, sand blasting, ultrasonic impact treatment, etc., are well-known to be beneficial for fatigue enhancement [31; 32]. Heat treatment is the best alternative method to enhance the fatigue life of Al alloys, as reported previously [33; 34].

The main objective of the work [35] was to investigate the effect of heat treatment on the fatigue behaviour of both notched and unnotched components under variable

amplitude loading conditions. Furthermore, the chosen heat treatment involved the stress relief (SR) occurred owing to the holding for 2 h at a temperature of 250 °C followed by water quenching to the room temperature. The selection of the heating temperature below 260-270 °C ensured the Si precipitation too.

The fatigue results under variable loading amplitudes were represented and it was evident that the SR series demonstrated an overall improvement in the fatigue strength (the fatigue strength has increased by 18 % for 106 cycles when comparing with as-built series). The residual stress relief and their subsequent stabilization were concluded the main factor for improving the fatigue strength.

The study [36] describes the experimental evaluation of the tensile and fatigue properties of AlSi10Mg samples produced additively within one SLM build cycle. The manufactured samples were processed by different heat treatments (HT) and the static and fatigue behaviour of AM-built AlSi10Mg specimens were studied. From the perspective of the high-cycle fatigue performance, the best HT concerns the T300 variant (300 °C for 2 hours and water quenched). It yields the highest fatigue strengths in high-cycle fatigue (HCF) region, despite the silicon network being decomposed, which results in lower tensile properties. If the low-cycle fatigue response is to be optimized however, the T200 series with artificial age-hardening at 200 °C for 2 hours / furnace and air cooled performs the best. Overall, any heat treatment seems to improve the fatigue response compared to untreated no-HT series. From the perspective of the heat dissipation during fatigue testing, the step self-heating test with increasing stress amplitudes was used to assess the regions of stabilized temperature for each load amplitude. The results show that though some hints of the bilinear dependency between stress amplitude and the observed temperatures can be detected and the knee point might relate to the fatigue limit position, a third region starting at higher stress amplitudes masks it very well. A consistent use of this solution for fatigue limit detection would require defining a criterion for clipping the stress-temperature dependency at the specific stress level.

The study [37] focused on the high cycle fatigue (HCF) domain response of SLM manufactured samples. The main objective of the work was to analyse the fatigue strength of samples coming from platforms with different level of the recycling the input powder, and to investigate the stability of SLM technology as regards this aspect. The effect of the printing powder recycling is questioned. Three different heat treatment setups were applied. Temperature of samples during the experiment was parallel monitored to describe the temperature changes during dynamic cyclic loading in order to estimate the fatigue life behavior in the cost-effective manner. Specifically, it was focused on the AlSi10Mg alloy processed by the SLM method under different heat-treatment conditions (T6 and direct aging (DA)). First, T6 heat treatment was applied, i.e., solution heat treatment at 520 °C for 2 h followed by water quenching; subsequently, the material was aged at 180 °C for 6 h

to obtain the T6 alloy. Second, the as-built alloy was not subjected to the solution heat treatment described above, but the aging treatment was carried out at 180 °C for 6 h to obtain the DA alloy. The S–N curves of the fatigue specimens in Fig. 2 show the number of cycles to failure at various maximum cycling stress. In this investigation, the S–N curves represent that the heat treatment with direct aging significantly improved the fatigue performance of the SLM AlSi10Mg alloy at all tested stress levels, with the best improvement at the lower stress levels. The fatigue limits estimated for the as-built, T6, and DA alloys were 160, 120, and 180 MPa, respectively. The fatigue limit of the DA alloy increased by as much as 20 MPa compared with that of the as-built alloy, as opposed to that of the T6 alloy, which decreased by as much as 40 MPa. These results show that certainly, under the same stress conditions, the fatigue properties of the DA alloy are superior to those of the as-built alloy.

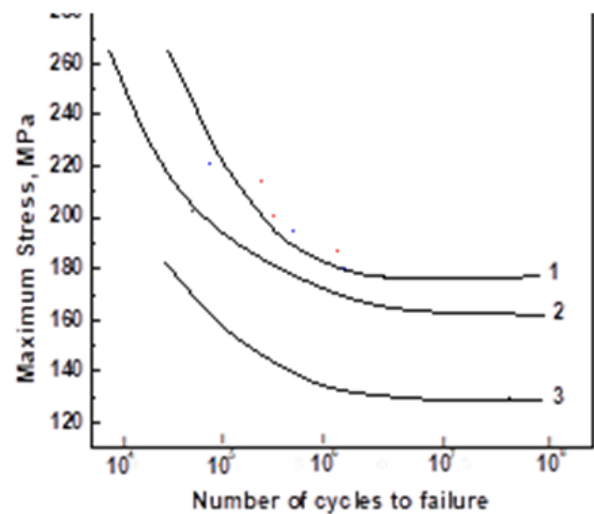


Fig. 2. Maximum stress variation by the number of cycles: direct aging (1); as-built (2), T6 (3) [37]

Evolution of the microstructure resulted in the modification of the fatigue properties of the investigated alloy. Predominantly, the fatigue properties were influenced by the morphology and size of Si particles controlled by using different heat treatment methods. The heat-treated DA alloy exhibited superior fatigue properties due to its cellular structural morphology characterized by the significant amount of the fine Si precipitates. Therefore, the formation and coarsening of the separated Si particles were responsible for the inferior fatigue properties of the as-built and T6 alloys.

Improving the fatigue behaviour of SLM aluminium alloy was postulated in [38]. It was investigated two types of samples. Batch 1 was tested without machining and Batch 2 was machined by turning to reduce the surface roughness; machining allowance was taken into consideration when building the samples by accounting for extra material removal (1 mm in diameter). Half the samples in each batch were heat-treated following a conventional T6 procedure. The samples were solution heat treated for 1 hr at 520 °C followed by water quenching to room temperature and then aged for 6 hrs at

160 °C. The as-built material showed good performance under cyclic loading. Machining the samples did not enhance the fatigue life at the higher stress levels but an enhancement was observed at the lower stress levels. On the other hand, HT considerably improved the fatigue performance of the material. The optimum fatigue life was achieved when the samples were heat-treated and machined. The enhancement in fatigue life via HT was attributed to the induced ductility, microstructure transformation, and reduction of residual stresses. For instance, the fatigue life of both as-built and machined samples was similar at the higher maximum stress levels, but at maximum stress levels below 157 MPa some of the machined samples started to survive the pre-defined 3×10^7 cycles cut off limit.

In [39] after the samples were SLM printed, some of them were heat treated with different heat treatment systems: stress relief annealing at 300 °C for 2 h, furnace cooling (SR); solution treatment at 530 °C for 1h, water quench (ST); some of the solution treatment samples followed by artificial aging at 170 °C for 12 h (T6). It was concluded that as-built samples display the highest fatigue property, ST treatment samples display the lowest fatigue property, heat treatments reduce fatigue property. The change of the fatigue property is caused by the microstructure evolution. As-built samples display the highest fatigue property due to the continuous network dendrite Si. The morphology and of the Si particles size is contributed to the fatigue property. HT changes the microstructure, dendrite Si breaks into separated particles. The formation and coarsening of the

separated Si particles result in the decrease of fatigue property.

Hot Isostatic Pressing (HIP). Previously, it was established for the cast aluminum alloys that HIP treatment at 520 °C and 100 MPa for 2 hours led to reduction in the volume fraction of the porosity with increasing the degree of the fatigue resistance [40; 41], it the effect of the post 3D-printing treatments, such as stress relief at 300 °C (SR), and HIP treatment (at 250 °C, and 500 °C) of the samples fabricated by SLM on the fatigue resistance was investigated. Fig. 3 shows the side (X) and the top (Z) macrostructure images of the samples after different post 3D-printing treatments. The side views (Figs. 3 a, c and e) demonstrated the “fishscale” morphology and the melt pools. The top views (Figs. 3 b, d and f) show the track segments because the laser beam rotation during printing. After SR+HIP treatment at 500 °C the almost homogeneous macrostructure is observed. The “fishscale” morphology was completely expunged (Fig. 3 g) and the track segments were hardly visible (Fig. 3 h).

Analysis of the S-N curves showed that the fatigue limit of the samples after SR+HIP treatment at 250 °C was slightly lower than that of the samples after SR, while samples after SR+HIP at 500 °C displayed the lowest fatigue resistance. Mechanical properties derived from the stress-strain curves and values of micro-hardness of the samples after various post treatments are summarized in Table. It was observed, that SR and HIP cycles decrease the yield strength, hardness and fatigue limit. The SR and HIP treatment

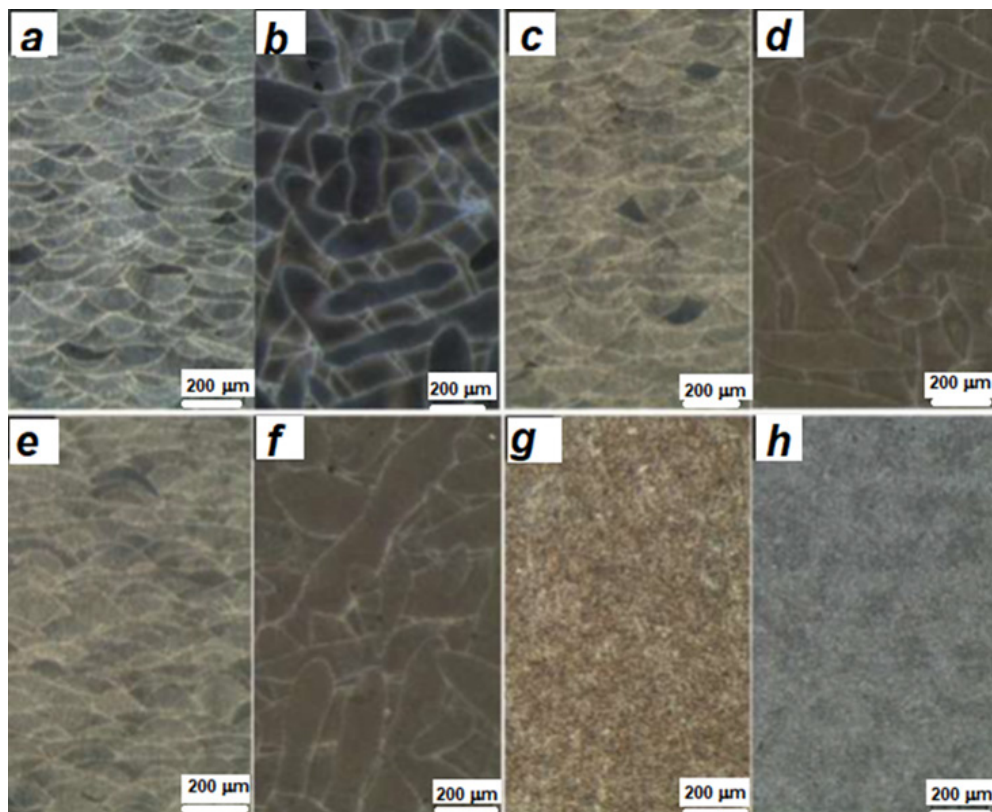


Fig. 3.

Typical macrostructure of the 3D-printed samples after different post treatments: as-built (AB), side (a) and top (b) views; after SR, side (c) and top (d) views; after SR+HIP at 250 °C, side (e) and top (f) views; after SR+HIP at 500 °C, side (g) and top (h) views [41]

Mechanical properties of AM-SLM AlSi10Mg specimens after various post processing treatments [41]

Post processing treatment	Yield stress, MPa	Fracture stress, MPa	Elongation at fracture, %	Microhardness HV, MPa
As built	241	384	6	1196
SR	205	253	18	931
SR+HIP 250 °C	186	233	22	892
SR+HIP 500 °C	115	141	35	520

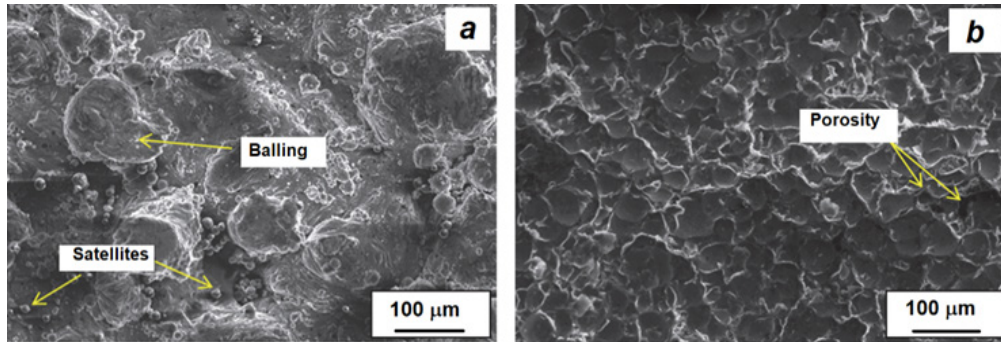


Fig. 4.

Surface morphology of (a) as-printed and (b) as sand-blasted samples [42]

at 500 °C resulted in the lowest fatigue resistance due to significant microstructural changes. Samples after SR+HIP treatment at 500 °C displayed the lowest fatigue resistance due to microstructure coarsening and reduced mechanical properties [41].

Sand-blasted samples. In [42] after 3D-manufacturing SLM, the samples were sand-blasted by using the ceramic complex particles ($ZrO_2+SiO_2+Al_2O_3$) at the exposure time of 2 min at 5 bar. The sand had a size distribution in the range of 63–125 μm.

The surface morphology of the as-printed as well as sand-blasted samples is shown in Fig. 4. The following structural features are observed: the as-printed surface has the irregular, with a lot of the satellites and/or balling; on the contrary, the sand-blasted sample shows the more homogeneous surface morphology, with remarkably reduced imperfections, even though small porosities can be revealed. The surface roughness (R_a) before and after sand-blasting are 13.2 μm and 7.0 μm for the as-printed and the sand-blasted samples, accordingly. In fact, this post-treatment determines a strong decrease of the surface roughness R_a as compared to the as-fabricated condition (approximately a reduction of 50 %). An evident improvement of surface finishing was observed after sand-blasting, which also lead to the presence of compressive residual stress on the external surface of samples. Also, it was found that the tested material exhibits good fatigue resistance, supporting the positive role of sand-blasting as the simple post-processing treatment.

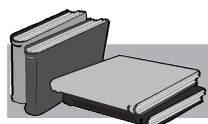
Shot-peening. Previously the positive effect of the shot-peening (SP) on the of cast aluminum alloys fatigue resistance has been widely investigated and discussed [43–45]. Accordingly, the objective of the work [46] the effect of the SP on the fatigue resistance of AlSi10Mg samples fabricated by the SLM technique was studied.

SP was performed using the balls of two types: the steel balls – S110 utilizing an Almen intensity of $I = 5''A$, and the ceramic balls – Z210, utilizing an Almen intensity of $I = 12.2''N$. The samples of the following types were studied: without SP; SP with steel balls; SP with ceramic balls; polished before SP with steel balls; polished before SP with ceramic balls; casting polished. The effect of shot peening of stress relieved AM-SLM AlSi10Mg specimens on their fatigue resistance was investigated. The main conclusions were as follows: the optimal mechanical and electrochemical polishing of the shot-peened sample surfaces was that removed about 25–30 μm from the surface. It led to significant improvements in the fatigue resistance, especially for a high cycle fatigue regime.

Ultrasonic impact treatment consisting in the multiple high-frequency impacts by the treated surface and producing the low-roughness finished surfaces and nanocrystalline near-surface layers in metallic materials can be also expected beneficial in fatigue life enhancement of AM-SLM AlSi10Mg specimens. These expectations appear well substantiated accounting for the recently shown improvement in fatigue performance of the powder metallurgy titanium alloys owing to compressive stresses, microstructure changes and decreased surface roughness and residual porosity [29; 46].

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Втомна міцність сплаву AlSi10Mg, отриманого шляхом адитивного виробництва: ефекти постобробки

Адитивне виробництво і, зокрема — 3D-друк металами та сплавами, активно розвивається упродовж останніх років. Все більш складні деталі можуть вироблятися із залученням великої кількості сплавів. Одним з найбільш поширених та універсальних методів 3D-друку є селективне лазерне плавлення (СЛП). В свою чергу, одним з найбільш придатних та широко застосовуваних сплавів для СЛП є сплав AlSi10Mg. Він відноситься до класу ливарних сплавів і використовується в багатьох галузях промисловості через високу питому міцність, корозійну стійкість, низький коефіцієнт термічного розширення та невисоку вартість. Для більшості адитивно виготовлених металевих деталей важливою проблемою, яку потрібно вирішувати, є забезпечення достатніх показників втомної міцності, що пов'язано з відносно високою дефектністю поверхонь одержуваних виробів.

Огляд присвячений аналізу способів постобробки СЛП-надрукованих виробів зі сплаву AlSi10Mg, які здатні підвищити їхню втомну міцність. Відмічається, що до основних причин знижених показників втомної міцності, крім якості поверхні, відносяться залишкові напруження, викликані точковими перегрівками та охолодженнями мікрооб'ємів металу під час формування виробу.

Термічна обробка, зокрема — низькотемпературний відпал для зняття напружень за температури 250 °С з подальшим охолодженням у воді, сприяє підвищенню втомної міцності на 18 %, а гартування та старіння за режимом Т6 — збільшує межу навантажень на 20—40 МПа. Це пояснюється перебігом процесу сфероїдизації частинок кремнію.

Гаряче ізостатичне пресування знижує пористість зразків, зменшує залишкові напруження в них та максимально гомогенізує структуру, проте призводить до зниження мікротвердості, межі текучості та втомної міцності.

Піскоструменева обробка сумішшю оксидів алюмінію, кремнію та цирконію сприяє зниженню шорсткості поверхні в півтора-два рази, майже повністю усуває поверхневу пористість та забезпечує стискаючі напруження, що в комплексі підвищує втомну міцність.

Відмічено перспективність ультразвукової поверхневої обробки поверхні 3D-виробів, яка чинить вплив, подібний до піскоструменевої обробки, проте є більш ефективною.

Ключові слова

3D-друк; СЛП, AlSi10Mg; втомна міцність; поверхнева обробка; термічна обробка.