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Characteristics of Titanium Alloys used in the SLM Additive Technology

Abstract: The article presents an overview of titanium alloys presently used in the Selective Laser Melting (SLM) technology. In the article, particular attention is paid to obtained strength properties and structural transformations of materials used in the tests. The article also presents the application potential of individual alloys and discusses the SLM additive technology.

Keywords: titanium alloys, Selective Laser Melting, SLM, additive technologies

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Introduction

The additive technology based on the selective laser melting (SLM) method was developed in the second half of the 1990s. The SLM technology was both inspired by and based on the stereolithography, a technology "born" in the late 1980s. Initially, the SLM technique, characterised by the obtainment of elements on the layer-after-layer basis was used in the making of prototypes. However, with the passage of time accompanied by the growing demand for small numbers of specific products as well as the need for the making of specifically-sized elements within one process, the SLM technology "revealed" its ability to reduce both the time and the cost of production [1].

Over the past twenty years, the SLM technology has enabled the making of elements using both pure titanium and its alloys, constituting the primary structural material in various industries for more than sixty years. The use of titanium alloys results predominantly from their high strength, low density, high resistance to cracking and corrosion as well as high biocompatibility [2–4]. The selective laser melting technology enabled replacing the multiple application of conventional technologies used to make elements, i.e. forging, casting and rolling as well as machining technologies used to obtain ultimate shapes and sizes [3]. The most popular titanium alloy as regards the SLM technology is commercial alloy Ti6Al4V, yet its popularity results primarily from its availability. The group of presently used titanium alloys includes Ti6Al2Zr1Mo1V, Ti13Nb13Zr, Ti35Zr28Nb, Ti37Nb6Sn and

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Ti47Cu38Zr7.5Fe2.5Sn2Si1Ag2, the characteristics of which are presented in the remainder of the article.

Selective Laser Melting Technology

The SLM technology is very similar to selective laser sintering (SLS), yet, because of significantly higher energy density, SLM enables the entire melting of metallic powders used in the process, which, in turn, translates into the obtainment of density close to theoretical [5]. Figure 1 presents a simplified schematic diagram of the selective laser melting technology. The most important elements of the SLM additive technology include a laser of appropriately high power, enabling the melting of a layer (usually 30 µm in thickness) of powder and a scanning system enabling the programmed movement of the laser beam. Powder is usually fed from a cylindrical container fixed to the work table. The movement of a piston by a specific distance triggers the supply of a portion of powder sufficient to create the appropriate thickness of a layer by the advance movement of a distributing strip. During the movement of the piston containing the material, the piston acting as the fixing plate is moved up by the height of one layer of powder. During the entire process the movements of the pistons are correlated. The process finishes once a given element has been made. Afterwards, a piston with the element fixed to it is moved out and, following the removal of powder from the station, it is possible to take out the ready element. Usually, the SLM device chamber is equipped with conduits supplying shielding gases and enabling work with oxidisable materials.

The crucial aspects of the SLM technology include the appropriate adjustment of process parameters (significantly affecting the microstructure), mechanical properties and the relative density of an element being made. The most important parameters affecting the density of energy supplied to a powder layer and enabling the entire melting of the charge material include laser power, scanning rate and the laser beam diameter. Depending on the type of material used in 3D printing as well as the size of powder particles and the height of powder layer, the power used in the process is restricted within the range of 60 W to 370 W, the scanning rate is restricted within the range of 200 mm/s to 1250 mm/s, whereas the laser beam diameter is restricted within the range of 50 µm to 140 µm [6–10].

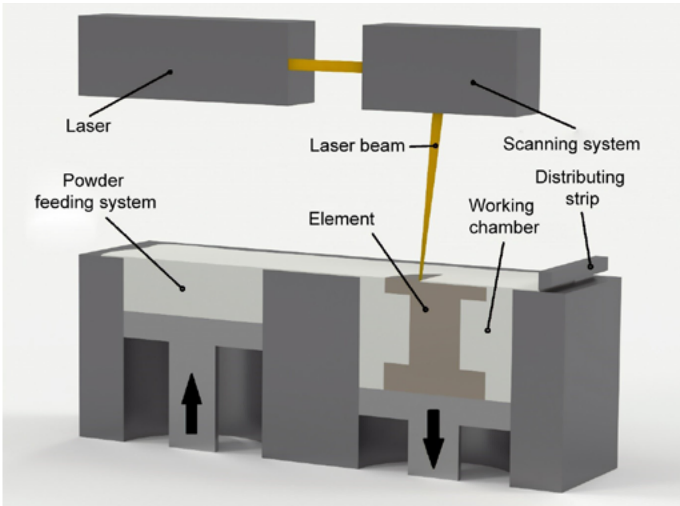

Fig. 1. Simplified schematic diagram of the SLM technology [5,11–17]

Titanium alloys

Alloy Ti6Al4V

The most popular titanium alloy used in the selective laser melting technology is alloy Ti6Al4V, owing its popularity, particularly in the aviation industry and implantology, to low density, high mechanical properties and high corrosion resistance [18]. Table 1 presents mechanical properties of Ti6Al4V. Elements made using the SLM technology are characterised by the low anisotropy of properties in the scanning direction and in the layer addition direction. In terms of the scanning direction, the tensile strength of solid specimens is restricted within the range of 937 MPa to 1246 MPa. As regards the tension in the layer addition direction, the tensile strength is restricted within the range of 1145 MPa to 1420 MPa. Recently, particular attention has been given to elements made using the SLM technology and characterised by high porosity. In all likelihood, because of the low Young's modulus and the strength comparable to that of bones, the aforesaid structural elements could find applications in the biomedical industry [19,20]. High mechanical properties of elements made of alloy Ti6Al4V using the SLM technology result primarily from structural transformations occurring in the material during melting followed by very fast cooling. The obtained non-equilibrium martensitic structure α' is characterised by high tensile strength and low elongation [21].

Table 1. Selected mechanical properties of titanium alloy Ti6Al4V subjected to SLM

Arrangement	R_m [MPa]	R_p [MPa]	Modulus of elasticity [GPa]	Elongation [%]	Pos.
longitudinal	1246 ± 134	1150 ± 67		1.4 ± 0.5	[22]
transverse	1421 ± 120	1273 ± 53		3.2 ± 0.5	
stress relieved – longitudinal	1032	961	127	2.7	[23]
transverse	1145 ÷ 1237	1102 ÷ 1161		7.6 ÷ 12.5	[24]
longitudinal	1091 ÷ 1202	1029 ÷ 1121		7.8 ÷ 12.8	
longitudinal	1103.16			4.09	[21]
longitudinal	1274 ± 26	1047 ± 23		10 ± 1	[25]
transverse	1219 ± 32	1043 ± 18		12 ± 1	
longitudinal	937.5 ± 1.3	897.0 ± 2.0	108.3 ± 5.4	16.8 ± 1.9	[20]
longitudinal – various porosity	44.9 ÷ 237.5		1.93 ÷ 5.26		[19]
longitudinal – various irregularity	105.8 ÷ 158		3.22 ÷ 3.92		
longitudinal – porosity	194.9 ± 1.9	146.6 ± 2.8	10.4 ± 0.2	7.8 ± 0.6	[20]
longitudinal – surface porosity	661.1 ± 3.3	600.7 ± 2.8	73.4 ± 0.8	15.1 ± 1.3	

Alloy Ti13Nb13Zr

Alloy Ti12Nb13Zr was developed in the early 1990s and is considered to be similar to alloy β. Because of the non-toxic combination of chemical elements and the low modulus of elasticity restricted within the range of 40 GPa to 80 GPa, the alloys was successfully used in biomedical engineering (to make implants) [26]. Table 2 presents selected mechanical properties characteristic of alloy Ti13Nb13Zr subjected to the SLM process. The authors revealed slight anisotropy in the powder layer melting direction (horizontal) and in the layer addition direction (vertical); the reason for the above-named anisotropy being the presence of twin boundaries in the structure in the vertical direction and the arrangement of beta grains in the privileged direction in the longitudinal position. The structure of test specimens revealed the predominant presence of phase β and acicular martensite α' [6,27–29]

Table 2. Selected mechanical properties of titanium alloy Ti13Nb13Zr subjected to SLM

Arrangement	R_m [MPa]	R_p [MPa]	Modulus of elasticity [GPa]	Elongation [%]	Pos.
longitudinal	1106 ± 10	887 ± 10		3.1 ± 0.3	[29]
transverse	996.19	794.63		5	[6]
longitudinal	1020.73	832.78		6.5	
transverse	996.19 ± 13	794.63 ± 15	65.28	5 ± 0.3	[28]
longitudinal	1020.73 ± 15	832.78 ± 20	66.23	6.5 ± 0.3	

Alloy Ti6Al2Zr1Mo1V

Alloy Ti6Al2Zr1Mo1V is considered to be similar to alloy α. Alloys of the aforesaid type were designed to withstand difficult and high-temperature conditions, hence their popularity in the aviation industry. Under normal conditions, alloy Ti6Al2Zr1Mo1V subjected to the SLM process reaches a tensile strength of 1442 MPa combined with an elongation of 9.5%. In turn, at a temperature of 500°C, the above-named values amount to 990 MPa and approximately 15.3% respectively. The high mechanical properties of the alloy result from the presence of numerous nanometric twin boundaries (in the structure) and acicular martensitic structure α' [8].

Alloy Ti35Zr28Nb

A new biomedical material is alloy Ti35Zr28Nb. In terms of structure, this alloy is treated as alloy β. Solid elements made of this alloy in the SLM process were characterised by a tensile strength of 612 MPa and 768 MPa (in the longitudinal and transverse arrangement, respectively) and an elasticity modulus of 57 GPa and 60 GPa. The modulus of elasticity of elements characterised by high porosity (reaching 83%) amounted to 1.1 GPa and 0.7 GPa, whereas their tensile strength amounted to 27 MPa and 8 MPa. A decrease in porosity would be accompanied by an increase in the aforesaid values, reaching 1.3 GPa and 1.0 GPa as well as 58 MPa and 45 MPa at a porosity of 50% (in the longitudinal and transverse arrangement, respectively) [7].

Alloy Ti37Nb6Sn

Publication [30] presents test results concerning specimens made of alloy Ti37Nb6Sn subjected to the SLM process. The above-named alloy is treated as an alternative to commercial titanium alloy Ti6Al4V. It is characterised by the presence of chemical elements non-toxic to humans and a relatively low modulus of elasticity. Table 3 presents selected mechanical properties related to various parameters of selective laser melting and a constant layer thickness of 0.03 mm. It was noticed that the supply of excessively high energy resulted in low strength, low ductility and increased porosity. In turn, the use of overly low energy resulted in a failure to melt Nb particles, reducing ductility through

Table 3. Selected mechanical properties of alloy Ti37Nb6Sn subjected to SLM [30]

Parameters h [mm]; P [W]; v [mm/s]; E [J/mm³]	R_m [MPa]	R_p [MPa]	Modulus of elasticity [GPa]	Elongation [%]
0.12; 225; 1200; 52.08	867	735	75.2	17.0
0.12; 275; 1200; 63.66	872	745	75.6	17.5
0.12; 225; 800; 78.13	874	743	74.7	21.0
0.05; 225; 1200; 125.00	892	775	66.2	27.5
0.05; 225; 800; 187.50	885	795	72.2	25.0
0.05; 350; 800; 291.67	834	642	75.5	10.0

h –laser beam diameter; P –laser power; v – scanning rate; E – energy density;

the propagation of secondary cracks. The appropriate adjustment of parameters enabled the making of elements characterised by high strength (small grains, few imperfections), low modulus of elasticity (colonies of martensite α”) and high ductility.

Alloy Ti47Cu38Zr7.5Fe2.5Sn2Si1Ag2

Alloy Ti47Cu38Zr7.5Fe2.5Sn2Si1Ag2 is rated among bulk metallic glasses and can be successfully used in the SLM technology. Due to the possibility of fast supercoiling, typical of the selective laser melting technology, it is possible to make fully amorphous elements of alloys susceptible to amorphous structure formation. The above-named alloys are characterised by a high vitrification temperature (T_g=659 K) and extensive areas of supercooled liquid (48 K). Elements made of alloy Ti47Cu38Zr7.5Fe2.5Sn2Si1Ag2 subjected to the SLM process are characterised by relatively high density restricted within the range of 99.5% to 99.7 %), a tensile strength of 1690 MPa and the module of elasticity amounting to 100 GPa. Taking into consideration obtained mechanical properties, the alloy can be successfully used in the aviation industry, whereas because of the favourable composition of alloying elements combined with appropriately adjusted parameters of the SLM process, it can also find applications in biomedical engineering [7].

Summary

The primary objective of the study was to present the extensive area of titanium alloys currently applied in the additive technology of selective laser melting. One of more important aspects related to the use of the SLM technology is the possibility of manufacturing elements of previously designed shapes and sizes within one process. The recent two years have seen considerable progress in the design of elements characterised by high porosity, which, among other things, has contributed to the reduction of the modulus of elasticity, thus enabling the application of such structures in biomedical engineering, for instance when making implants and bone loss-related scaffolding. Because of becoming similar to the tensile strength and the modulus of elasticity of the bone it is possible to avoid bone resorption. In addition, the last two years have seen the gradual departure from the use of commercial alloy Ti6Al4V as bodies of tested patients revealed elevated concentrations of vanadium and aluminium alloys, triggering various undesirable reactions of tissues and neurological disorder. The use of other titanium alloys, not containing toxic elements (Zr, Nb, Si), eliminates the above-presented side-effects.

The use of solid elements made of titanium alloys obtained in the SLM process makes them highly usable in the aviation industry. The primary reason is the obtainment of high mechanical properties combined with low density. Presently, the highest properties are obtained using bulk metallic glasses of appropriate chemical composition enabling the making of entirely amorphous materials during the selective laser melting process.

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