PROPERTIES OF THE BIOCOMPATIBLE TiAl6V4 MATERIAL PRODUCED BY DMLS

СВОЙСТВА БИОЛОГИЧЕСКИ СОВМЕСТИМОГО МАТЕРИАЛА TIAL6V4 ПРОИЗВЕДЕННОГО КОМПАНИЕЙ DMLS

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Abstract: *Direct Metal Laser Sintering[1] (DMLS) is a revolutionary technology that allows a production of fully functional metal parts directly from a 3D CAD data, eliminating the investment to production tools and technologies which brings considerable cost and time savings. Metal parts made by DMLS technology are fully comparable with casted or machined parts. A range of application of DMLS technologies is very wide – from prototypes, through short-run production to final products. Advantages of DMLS technology are arising along with complexity of parts – more complex geometry of parts (in terms of shape and occurrence of the detail) make DMLS technology even more economically effective.*

Keywords: TITANIUM ALLOY, DMLS, LASER SINTERING, 3D PRINTING, MICROSTRUCTURE

1. Introduction

A 3D CAD data of a part are imported into the procedural software of the printer EOSINT M 270[1]. Software designed to the data preparation allows choosing the appropriate thickness of production layers with regard to accuracy / resolution and speed of production (0.020 mm or 0.040 mm □ thinner layer means higher accuracy, but longer production time).

After the selection of powdered material (including the thickness of the layer) software assigns the proper technological parameters of construction and "cuts" the 3D data into layers which sends to the 3D printer EOSINT M 270. A steel platform is clamped into the working chamber of the 3D printer which has a function of a basement for the part constructing (Fig. 1). Afterwards, a dosing device sets the quantity of powder needed for one layer and then a shoulder with a ceramic blade spread on the surface of the steel platform a uniform layer of powder according to the chosen layer thickness. In the impact point of a laser beam, the powder is locally melted; the base layer is “melted-through” and then it solidifies into the solid state.

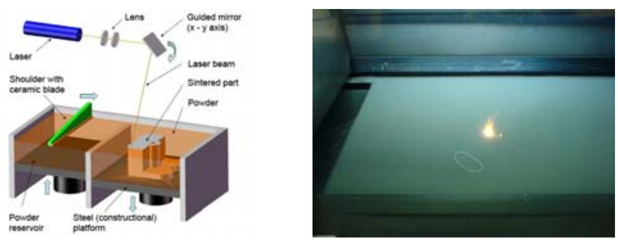

***Fig. 1** Working principle of 3D the printer EOSINT M 270[1].*

Energy of the laser beam locally melts the metal powder[1] only in contour of the cut which is defined by the intersection of the plane (layer) of the product body (3D CAD model). A correct position of the part is very important during a fabrication. The supporting structure (anchored on the base steel platform) is used to ensure the correct part position. Metal powder is thoroughly melted by the laser and ensures a perfect close coupling of deposited layers. Powerful 200 Ytterbium (Yb)-fiber “dual-spot” laser is able to produce even small construction features in fine resolution, fabrication of the physical model is faster thanks to the higher energy density of the laser beam. The laser beam is precisely driven in the X and Y coordinates, Z-axis is controlled by shifting of the platform layer when the layer is created. This system allows accordance with geometrical tolerances of shape in the range of ± 0.1 mm. Workspace of 3D printer EOSINT M270 is 250 x 250 x 215 mm.

2. Materials for Production of Prototype Parts[1]

A wide range of metal powders (from light alloys through steels to super-alloys and composites) is currently available for DMLS process and other new materials are under development. Table 1 lists mechanical properties of selected powder materials.

***Table 1:** Mechanical properties of selected powder materials[1]. *Note: Values in brackets are valid for heat-treated material.*

	Stainless steel EOS GP1	Martensitic steel EOS MS 1	Bronze-nickel alloy DM 20
Min. wall thickness [mm]	0,4	0,4	0,6
Speed of fabrication [mm^3/min^{-1}]	2-5	2-4	10-20
Residual porosity [%]	-	-	8%
Yield strength Rm [MPa]	900	1100 (1950*)	400
Proof stress Rp0,2 [MPa]	500	1000 (1900*)	200
Modulus of elasticity [GPa]	190	180	80
Abrasive hardness	23-33 HRC	36-39 (50-54*) HRC	120 HV
Max. working temp. [°C]	550	400	400

Titanium EOS Ti64 / Ti64ELI

Subject of research was TiAl6V4 alloy in the form of the fine powder. This light alloy (see Fig. 2) has excellent mechanical properties Tab. 2 and corrosion resistance in combination with low specific weight and biocompatibility. The material is mainly used in aviation, in the manufacturing of racing cars and in medical applications (manufacturing of implants, see Fig. 3).

***Table 2:** Mechanical properties of TiAl6V4 alloy[2].*

Mechanical properties	RP method - TiAl6V4	Hot formed TiAl6V4
Yield stress [MPa]	910 - 960	860 - 965
Yield strength [MPa]	970 - 1030	930 - 1015
Rockwell hardness [HRC]	30 - 35	30 - 35
Elongation [%]	12 - 16	10 - 14
Vibration fatigue limit/no. of cycles [-]	$> 1.10^{7}$	$> 1.10^{6}$
Elastic modulus [GPa]	120	114

***Fig. 2** Fine powder of TiAl6V4.*

***Fig. 3** Tibial knee component implant.*

Titanium alloys, their properties and application

Pure titanium[3,4] (melting temperature 1668 ° C) has 2 allotropic modifications3,4. An α phase is stable up to the transformation point (882 ° C) and it has the close arrangement of atoms in a hexagonal lattice (hcp). For higher temperatures a β phase has a cubic body centered lattice (fcc). Among the elements stabilizing the α phase belong C, O, N and especially Al, which forms along with Ti the solid solution, containing up to 26% of Al (mostly used max. 7% Al □ brittleness and poor ductility).

Two-phase alloys α+β contains Al (stabilizing function of the α phase) and further elements for stabilization of the β phase, particularly V, Mo (Cr, Fe and Mn).

Single-phase β alloys can be obtained by alloying of Ti by the mentioned elements or their combination. A significant stabilizing effect (usually if the higher concentration of component is achieved) of ingredients explains the excellent solubility in Ti, in full range of equilibrium diagrams (V, Mo).

Properties of titanium and its alloys

Mechanical properties of titanium[3,4] depend on the content of impurities. The main impact to the properties has following elements □ oxygen, nitrogen, hydrogen, carbon, iron, boron, beryllium, aluminum and rhenium. Hydrogen reduces the notch toughness; oxygen affects an increase of the yield stress and strength but also worsens its plastic properties. Carbon declines plasticity of material and increases the modulus of elasticity to the content of 0.5% C. Frictional properties of Ti determined by the coefficient of friction, abrasion and seizure susceptibility are also very important unlike other materials Ti has no usual layer of oxides to prevent contact areas from local friction welding.

Titanium is chemically very active metal, but on the other hand it is highly resistant to corrosion. Only four inorganic acids have a corrosive effect on the pure Ti □ HF, H_2SO_4, H_3PO_4 and HCl. At higher temperatures it has less resistance against further concentrated organic acids: oxalic, formic, trichloroacetic and trifluoroacetic.

All of the alloys have higher thermal expansion and thermal conductivity reaches only 30 to 60% of the value of pure Ti. For some of the alloys, the warm strength can be increased in terms of the heat treatment (in limited temperature range). In the graphs in Fig. 4 and Fig. 5, the change of the properties depending on temperature in annealed and hardened state for alloy TiAl6V4 is observed.

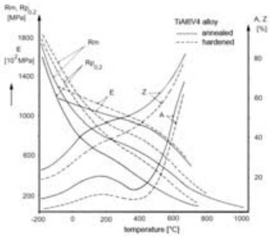

***Fig. 4** Dependence of mechanical properties on the temperature[4] .*

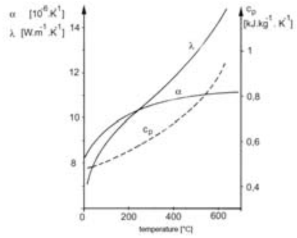

***Fig. 5** Change of thermally-physical properties of the alloy[4].*

3. Results

In this part[2,3,4] of the paper are presented the most important properties of tested titanium alloy TiAl6V4.

Structure of AlTi6V4 alloy made by hot forming

Structure of a hot formed material intended for machining, with a reduction of 47% at 970 ° C is shown in Figures 6 and 7. Hardening was carried out in air at temperature of 700 ° C, cooling time 2h; hardness of the material was found 33 HRC.

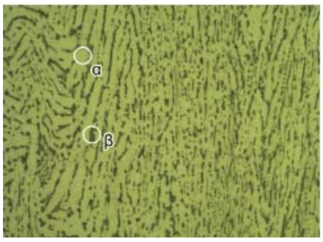

***Fig. 6** Structure of hot formed alloy TiAl6V4 – 33 HRC; LM; 500x.*

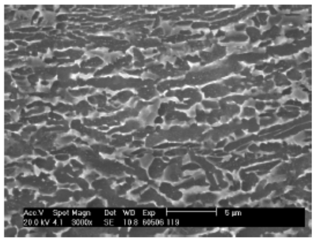

***Fig. 7** Structure of hot formed alloy TiAl6V4 – 33 HRC; SEM; 3000x.*

Structure of the hot formed material intended for machining, with a reduction of 21% at 970 ° C is shown in Figures 8 and 9. Hardening was carried out in air at temperature of 700 ° C, cooling time 2h; hardness of the material was found 31 HRC.

Fig. 10 shows the structure of hot formed alloy AlTi6V4 intended for machining, heat-treated by homogenization annealing. Hardening was carried out in air at temperature 950°C, cooling time 1h and again warming up to 700°C, cooling time 2h in air.

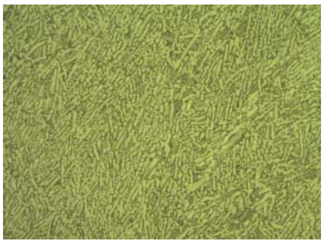

***Fig. 8** Structure of hot formed alloy TiAl6V4 – 31 HRC; LM; 200x.*

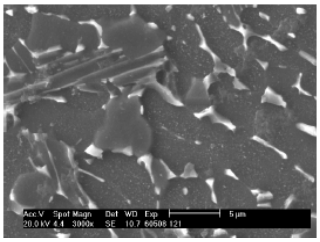

***Fig. 9** Structure of hot formed alloy TiAl6V4 – 31 HRC; SEM; 3000x.*

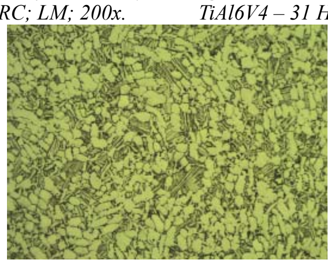

***Fig. 10** Structure of hot formed alloy TiAl6V4, homogenization annealed – 30 HRC; LM; 200x.*

Alloy structure TiAl6V4 – sample piece

The sample piece was produced of the TiAl6V4 alloy substrate by DMLS technology. The substrate (Fig. 11) mainly contains globular particles of a different size (maximal diameter 40 μm, see Fig. 12) and agglomerates combined of particles of diameter 1 μm (Fig. 13).

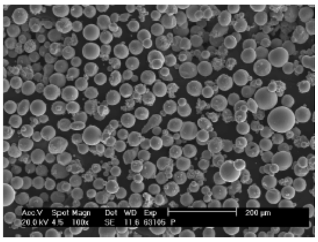

Fig. 11 *Substrate; alloy TiAl6V4 made by DMLS technology; 100x.*

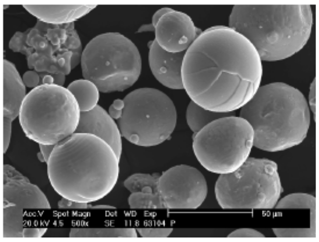

Fig. 12 *Globular particles; alloy TiAl6V4 made by DMLS; 500x.*

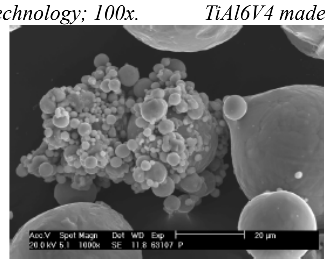

Fig. 13 *Agglomerates of particles; alloy TiAl6V4 made by DMLS technology; 1000x.*

A hardness of the samples made by DMLS technology was even higher (34 HRC) than a hardness of hot formed material (max. 33 HRC). The samples for material analysis were taken of the sample piece by a standard manner and a structure was developed chemically by Keller's Reagent etchant on the surface oriented perpendicularly to z-axis as well as on the surface oriented parallel to z-axis and the microstructure of cross section (Figs. 14, 15) is two-phased coarse-grained with sporadic occurrence of pores.

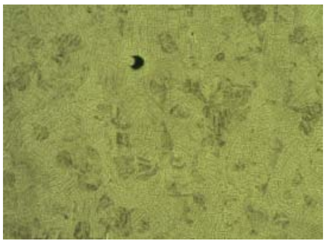

Fig. 14 *Microstructure of cross-section; perpendicularly to z-axis; LM; 50x.*

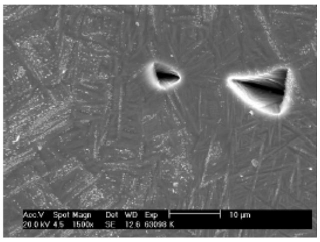

Fig. 15 *Microstructure of cross-section; perpendicularly to z-axis; SEM; 1500x.*

In the longitudinal section, a structure consists of elongated grains, which grow in the z-axis direction (Fig. 16, 17).

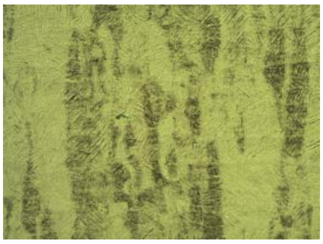

Fig. 16 *Longitudinal section consist of elongated grains; parallel to z-axis; LM; 100x.*

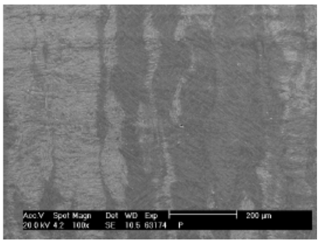

Fig. 17 *Longitudinal section consist of elongated grains; parallel; SEM; 100x.*

In the pictures above (Fig. 16 and 17) is shown the lamination of the powder and its fusion (contoure). A detail of these contours is well documented in Figs. 18, 19, 20.

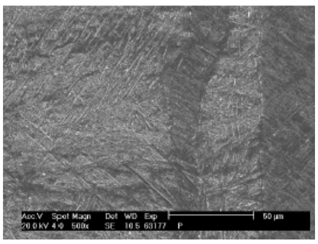

Fig. 18 *Lamination of the powder and its fusion; SEM; 500x.*

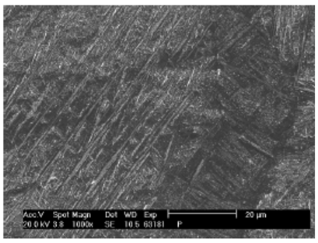

Fig. 19 *Lamination of the powder and its fusion - detail; SEM; 500x.*

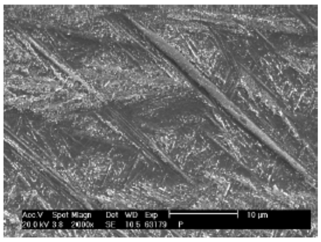

Fig. 20 *Lamination of the powder and its fusion - detail; SEM; 2000x.*

Due to the technology used for production of the part (DMLS method), the microstructure is influenced by the temperature and the rate of cooling of each layer. By the influence of rate of cooling, a non-diffusion transformation of the β phase (martensitic character) to the α phase is present. The final structure consists of the α phase lamellas with fine dispersion of hardening phase to V phase (Al10V and Al3V). Within the contour region (Fig. 20) and near to the pore (Fig. 15), the occurrence of hardened phase particles is only sporadic.

4. Discussion

Mechanical properties of Ti Alloys[3,4,5,6,7] are almost comparable to the properties of steel. Despite of the lower mass density, the Ti alloys are thermally and chemically more stable than steel.

A low thermal conductivity of Ti alloys causes a degradation of machinability by the influence of heat concentration in the cutting area. The thermally-physical properties of a workpiece and tools - cutting conditions (particularly speed, angle of cut, tool wear) and cooling (especially when grinding) affects a distribution of temperature field.

High temperature gradients in the surface layer during a machining process allows generation of the residual stress, due to uneven thermal expansion and contraction, as well as changes in structure from the effects of temperature and chemical processes.

5. Conclusion

DMLS method gradually acquires a position for rapid and accurate production of fully functional prototype parts or final products for different kinds of application. A 3D printing process creates highly durable, yet delicate components that are used for many industries, including aerospace, automotive, electronic or wrapping industry and medicine as well.

The field of DMLS technology is very broad and constantly growing due to the fact that the technology is relatively new (about 15 years). Potential of technology DMLS has not been investigated yet. Along with increasing of speed of 3D printer and expanding number of materials, area of the technology applications is increasing as well.

EOSINT M 270 equipment was installed in the Czech Republic for the first time in February 2007. The equipment was covered within the project "Establishment and development Cluster OMNIPACK" which is co-financed by the state budget and EU Structural funds. Detailed technical information about EOSINT M 270 can be also found at www.innomia.cz.

Acknowledgements

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