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direct metal laser sintering, 3Dprinting, 17-4PH stainless steel

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CHARACTERISTICS OF PRODUCTS MADE OF 17-4PH STEEL BY MEANS OF 3D PRINTING METHOD

Abstract

The article presents the results of tests of 17-4PH steel fabricated by means of the method consisting in laser additive manufacturing (LAM) – direct metal laser sintering (DMLS). This grade of steel is characterized by excellent stress corrosion resistance in the first place and is applied as construction material in chemical, aircraft, medical or mould making industry. 3D metal printing is a relatively new method enabling significant change of structural properties of these materials at printing parameters predetermined by printers manufacturer for "offline" printing mode. In order to achieve this goal, the authors have carried out the analysis of chemical composition, SEM tests and the tests of products surface roughness. Furthermore the products have been subjected to X-ray analysis by means of computed tomography (X-ray CT). Structural discontinuities have been found in upper layer and inside printouts subjected to tests.

1. INTRODUCTION

Additive manufacturing technologies called RapidPrototyping techniques occurred about 30 years ago. Initially, they were applied in aircraft and automotive industry where there is a need to apply metal elements characterized by complex shapes and high precision of inner structure. Additive manufacturing

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method of metal products fabrication by means of laser has been invented by Ciraud in the year 1971 (Borsuk-Nastaj & Młynarski, 2012; Mazzoli, Moriconi & Pauri, 2007).

This technology was based on direct fabrication of successive layers of 3D structures previously designed in computer aided design process. These structures can be tested and modified before engineering design works. The assumptions of this technology proposed by Ciraud have been applied till nowadays, and the process has been developed in the form of 3D printing technology thanks to modern CAD design technologies and laser technology.

Additive manufacturing methods are used for sintering of wide spectrum of metallic powders e.g. light alloys, titanium alloys, steel alloys and Co and Cr superalloys as well as polymer materials (e.g. polyamide) or ceramic and composite materials. This technology enables the fabrication of single elements or small series of elements in accordance with individual market demands, ensuring the forming of cavities, undercuts and inner channels which could be difficult or even impossible by means of conventional methods (Atzeni et al., 2016; Dobrzański & Matula, 2012; Pal, Tiyyagura, Drstvenšek & Kumar, 2016).

The latest technology used for making of complex shapes by means of metallic powders selective melting method consists in DLMS process (Direct Metal Laser Sintering). Thanks to DMLS technology, it is possible to obtain repeatable strength parameters of elements being fabricated. The essence of DMLS technology is the making of complex shapes which could be impossible even by means of casting methods and using difficult-to –cut materials.

The functioning principle of DMLS machines (Fig. 1) consists on application of a layer of precisely composed metallic powder by means of a blade on a working platform and then in selective sintering of successive layers of element being fabricated by means of near infrared laser beam (wave length of about 1064nm).

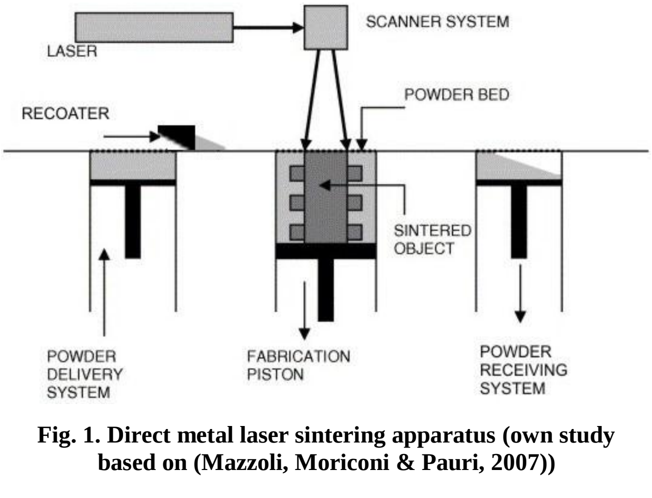

Fig. 1. Direct metal laser sintering apparatus (own study based on (Mazzoli, Moriconi & Pauri, 2007))

The whole process is carried out in protective atmosphere – most frequently in nitrogen or argon presence depending on reactivity of applied alloy. For example, aluminium and titanium alloys are processed in argon atmosphere and tool steels characterized by lower reactivity as well as Co and Cr superalloys are processed in nitrogen atmosphere.

2. RESEARCH METHODOLOGY

EOS StainlessSteel GP1 powder was the subject of tests. Composition of this powder is similar to US classification 17-4 PHand European 1.4542 stainless steel materials. This type of steel is widely applied in engineering applications requiring high strength and good plastic properties as well as wear and corrosion resistance e.g. in chemical, aircraft, medical or mould making industry. Circular specimens 6 mm thick with diameter Ø 30 mm were used for tests. The specimens have been fabricated in laser additive manufacturing (LAM) process by means of 3D printer for metals – EOSINT M280 supplied by EOS. The following parameters have been used in course of printing: laser power of 200W, layerthickness of 0.02 mmand laser spot size of 0.1 mm.

Chemical composition analysis has been carried out by means of Magellan Q8 emission spark spectrometer (Bruker, Germany). The tests were carried out on Fe130 detail testing channel used to complete 5 analyses (sparkings) for each specimen. The purpose of tests was to verify chemical composition with a confrontation with data declared by the manufacturer in technological sheets.

The surface of materials being tested has been subjected to analysis by means of PhenomProX scanning microscope (supplied by Phenom-World B.V.) and by means of Dektak 150 contact profile meter supplied by VeecoInstruments. Measuring needle radius was equal to 2 μm and load to 3 mg.

Additionally, the specimens have been subjected to X-ray analysis by means of computed tomography (X-ray CT) in order to check whether there are any structural discontinuities in the products made in LAM process. Therefore, SkyScan1272 computed tomography equipment (Bruker, Belgium) with XIMEA xiRAY11 camera and software package: Nrecon 1.6.10.1, CTVox 2.1.0 r741 and DataViewer 1.4.2 enabling the analysis of obtained images has been used for tests. The most important parameters which have been used for tests are: camera resolution of 1.6 μm, detector pixel number of 2688x4032, source voltage of 100kV, current of 100 μA, exposure time of 5300ms, rotation angle of 0.15°, average number of photos per rotation is equal to 6; the thickness of applied copper filter is equal to 0.11mm.

3. RESULTS AND DISCUSSION

The results of chemical composition analysis are presented in Tab. 1. The manufacturer – EOS company, does not indicate accurate information on carbon concentration percentage in furnished data except of maximum content. Measured average concentration is included in the scope declared by the manufacturer. In case of nickel, the concentration was slightly exceeded. Remaining elements contained in GP1 steel under analysis meet the requirements for 17-4PH steel. High content of Cu additive additionally increases stress corrosion resistance. In accordance with data (Thijs, Kempen, Kruth & Van Humbeeck, 2013), corrosion resistance of 17-4 PH is similar to this parameter of 18Cr-8Ni steel.

Tab. 1. Chemical composition of the tested GP1 (17-4 PH) stainless steel (masses %) (own study)

	C	Si	Mn	Cr	Mo	Ni	Cu	Nb	Fe
Tested 17-4 PH	0.044	0.717	0.686	15.9	0.118	5.272	4.806	0.274	71.84
SD	0.001	0,008	0.016	0.045	0.002	0.057	0.054	0.001	0.098
Manufactures	< 0.07	< 1	< 1	15–17.5	< 0.5	3-5	3-5	0.15–0.45	bal.

Direct metal laser sintering DMLS consists in laser beam scanning on the surface of thin layer of powder deposited on substrate (base plate). The laser beam is directed to the layer of powder distributed on the base plate. Then the laser is used to successively scan the first layer applied by scraper onto previously melted layer which becomes the substrate for the next layer (Yadroitsev, Krakhmalev & Yadroitsava, 2015; Lin et al., 2012). This process takes place in accordance with laser beam scanning direction (Fig. 2). After scanning, substrate is lowered and a new layer is deposited maintaining the powder surface in laser beam focusing plane. The process is repeated until the entire object is fabricated. A laser meltedtrack is created as a result of melted material surface tension. Laser beam penetration into substrate or into previously sintered layer causes an additional stabilizing effect for continuous creation of tracks (Yadroitsev, Gusarov, Yadroitsava & Smurov, 2010) but excessive depth of key hole penetration is not permitted in DMLS mode because such phenomenon can generate pores in the final 3D object as a result of weld pool collapse or gas bubbles in material (*Steelinox BV,*2016). Moreover, greater depth of laser beam penetration (melting depth) i.e. much greater than the thickness of sintered layer is also not useful for energy reasons (Yadroitsev et al., 2015).

SEM analysis of the surface after laser sintering (Fig. 2) indicated defects in the form of structural discontinuities in the area of weld face. Such phenomenon can be undesirable because the structural discontinuities in upper layer can play the role of micro-notches and, as a result of stresses concentration, these areas can jeopardize the reliability of the object being printed.

Surface roughness analysis (Fig. 3) indicates that elements printed at pre-determined parameters are characterized by significant surface area (Sa = 6.05 µm, Sq=7.56 µm, St=55.76 µm).

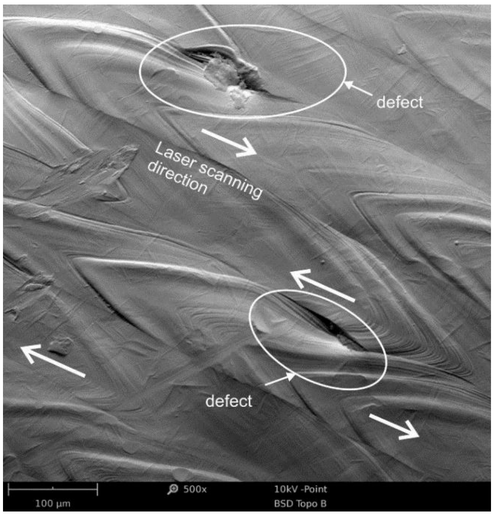

Fig. 2. SEM microphotographs of the tracks surfaces from 17-4 PH powder (own study)

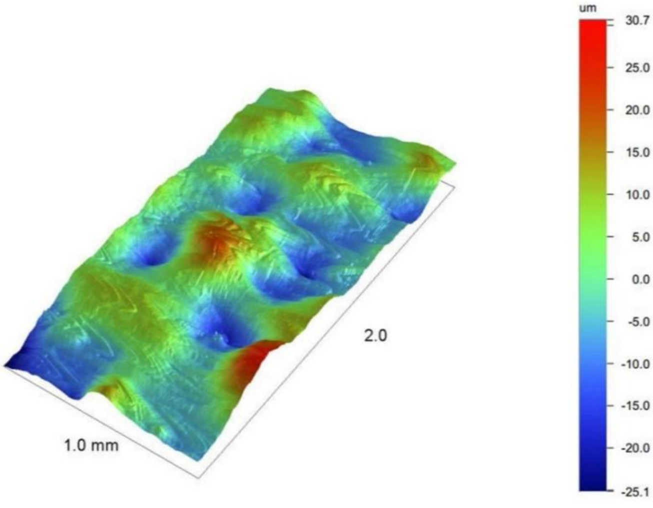

Fig. 3. 3. Dimension of surface roughness in 17-4 PH stainless steel (own study)

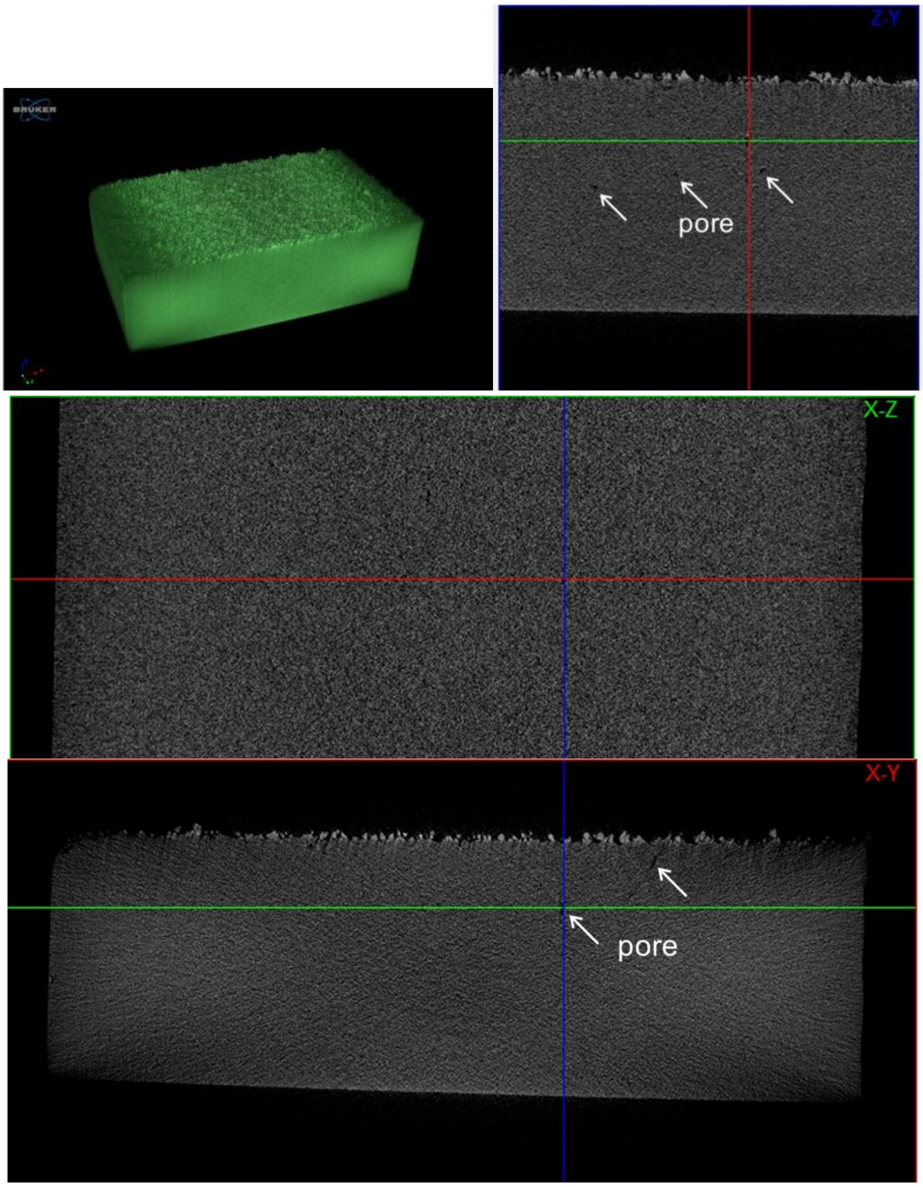

Fig. 4. Visualization of 3D specimen made of 17-4 PH and its cross-section in XYZ planes (camera resolution of 1.6μm) (own study)

Furthermore, the analysis of cross-sections carried out by means of X-ray computed micro-tomography disclosed a discontinuity on XY and ZY planes (Fig.4) in the form of pores exceeding the size of 5 μm. This is a particularly worrying phenomenon in the context of products made of 17-4PH steel applied in aircraft industry.

4. CONCLUSIONS

Thanks to the use of advanced additive techniques, it is possible to fabricate the products which could be difficult to fabricate by means of conventional methods i.e. casting or machining. Furthermore, these techniques make it possible to build complex cooling channels following the contour of an element in injection moulds inserts. Described technique makes it possible to design complex geometries with lattices structures in order to unload the components in aircraft and aerospace industry.

Optimization is required for selection of parameters for elements fabrication by means of direct metal laser sintering DMLS methods. Printouts of elements made of 17-4PH steel using a priori process parameters in "offline" mode in case of highly loaded products can be unsatisfactory because, as confirmed by X-ray analysis, they create the possibility of pores generation in material structure. Furthermore, the surfaces of the products fabricated by means of this method are characterized by significant surface area and accumulation of structural discontinuities is possible in upper layer; their effect can be compared to the effect of micro-notches. Therefore upper layer of such product should be additionally subjected to finishing (grinding or sandblasting). Chemical composition of printed products does not significantly differ from the powder composition declared by the manufacturer.

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