Science of Sintering, **44** (2012) 177-185

DOI:10.2298/SOS1202177E

UDK 622.785:666.9.019

Defectoscopy of Direct Laser Sintered Metals by Low Transmission Ultrasonic Frequencies

Zoran Ebersold[1], Nebojša Mitrović[2*)], Slobodan Đukić[2], Branka Jordović[2], Aleksandar Peulić[2]
[1] University of Applied Sciences, Postfach 110605, 86165 Augsburg, Germany
[2]Technical Faculty Čačak, University of Kragujevac, Svetog Save 65, 32 000 Čačak, Serbia

Abstract:
This paper focuses on the improvement of ultrasonic defectoscopy used for machine elements produced by direct laser metal sintering. The direct laser metal sintering process introduces the mixed metal powder and performs its subsequent laser consolidation in a single production step. Mechanical elements manufactured by laser sintering often contain many hollow cells due to weight reduction. The popular pulse echo defectoscopy method employing very high frequencies of several GHz is not successful on these samples. The aim of this paper is to present quadraphonic transmission ultrasound defectoscopy which uses low range frequencies of few tens of kHz. Therefore, the advantage of this method is that it enables defectoscopy for honeycombed materials manufactured by direct laser sintering. This paper presents the results of testing performed on AlSi12 sample.
Keywords: *Direct laser metal sintering; AlSi12; Ultrasonic defectoscopy; Quadraphonic transmissional ultrasonic defectoscopy.*

1. Introduction

Laser metal sintering, also known as a generative production procedure, is a process that enables the manufacture of individual prototypes of machine elements. This technology can be successfully used for the production of individual prototypes of small series machine elements [1]. Conventional subtractive processes that have significant circular and linear tool movements such as drilling, milling, polishing etc., are used for material modelling. Laser sintering uses three-dimensional CAD data to create one by one thin layers of metal powder [2]. Energy source for sintering are various types of lasers that have power range from 200 W to 400 W. Next to the gas lasers types HeCd, Ar or CO_2 laser, the most common used solid state lasers are Nd:YAG or YAG-lasers.

Laser sintering has a range of advantages:

- increasing the production procedure ("time to market") in just a few hours (5 to 20 cm^3 per hour), starting with a CAD construction of a complete product,
- high level of automation and high product precision,
- reduction of production and labour costs,
- new possibilities of logistics: reduction of storage expenses, ability to produce small series and a wide range of products,

*) **Corresponding author**: nmitrov@tfc.kg.ac.rs

- new business models: for example, manufacturing "spare parts on demand",
- product customization to serve individual needs ("customization").

Another very important feature of laser sintering is that it enables the manufacturing of the diverse structures with exceptionally complex geometries, external and internal. For instance, it is possible to produce mechanical elements with channels for cooling that are positioned parallel to the surface ("conformal cooling"), even in spiral geometry, etc.

Laser metal sintering is started with the introduction of stereolitography at the end of eighties [3]. Generative procedures of laser metal sintering can be divided into two categories:

- indirect laser metal sintering (ILMS),
- direct laser metal sintering (DLMS).

The indirect procedure is based on research carried out in the second half of eighties and at the beginning of nineties [4]. In ILMS procedure the first manufacturing step is selectively consolidating of metal powder that is mixed with polymers. In the second step, in the oven, using two levels of predefined asymmetrical temperature profiles, the final sintering of metal powders is achieved [5, 6]. The disadvantages of this procedure are longer production time and smaller number of alloys that can be processed. DLMS is a more recent procedure and comprises a single process step [7]. Currently, there are three leading direct laser sintering technologies:

- selective laser melting (SLM)
- direct metal laser melting (DMLM)
- laser cuising (LC).

All three technologies are based on the same physical principle, but they primarily differ in the type of material sintered [8-10]. Moreover, they also differ in the scanning strategy employed. An important term used in scanning strategy is the so-called „scanning vector" that designates the surface sintered by the lased head in a single step, without interruption.

Fig. 1 shows the laser sintering procedure [1]:

- samples are built on base 1a.1,
- tank 1a.2 supplies metal powder 1a.3 and adds one layer,
- laser 1a.4 consolidates the metal powder, connecting the active layer 1a.5 with the bottom layer,
- individual layers thickness 1a.6 ranges from 50 μm to 80 μm.

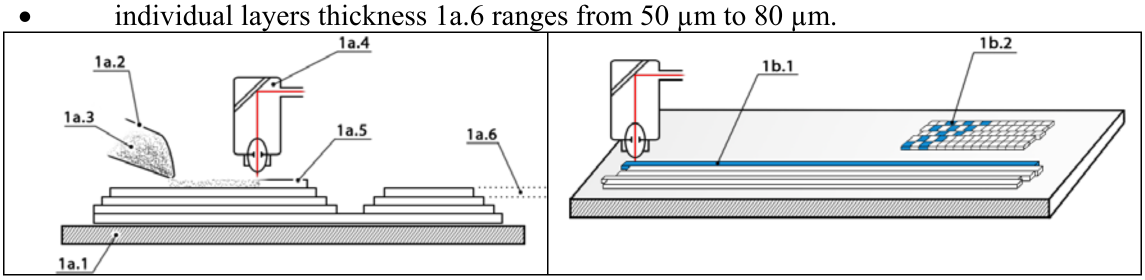

Fig. 1. Laser sintering procedure, a) side view b) scanning models

Fig. 1b.1 presents the scanning model where the length of the scanning vector is multiple times its width. Fig. 1b.2 illustrates the scanning model where the length and the width of the scanning vector are approximately equal, which is a particular feature of LC technology. Short vectors called "island type" scanning vector are observed. Various combinations of the scanning strategies presented are possible. Mechanical elements manufactured by laser sintering are often composed of many hollow cells. The cell structure ensures significant material savings, weight reduction and increased stiffness of mechanical elements [6]. The shapes of cells can be very diverse.

An important advantage of DLMS is its single procedural step. Therefore, the whole consolidation procedure inside the oven [7], that usually exist in the indirect process, is becoming obsolete, leading to a significantly shorter production time. Nevertheless, the direct method has a number of disadvantages: surface roughness, difficulties with tolerances, frequent insufficient hardness and insufficiently homogenized quality of products that differs among samples. Also, it controls a lager number of physical phenomena, as compared to ILMS. Consequently, in some cases cracks are formed and cell collapse sometimes occurs, as shown in Fig. 2a.

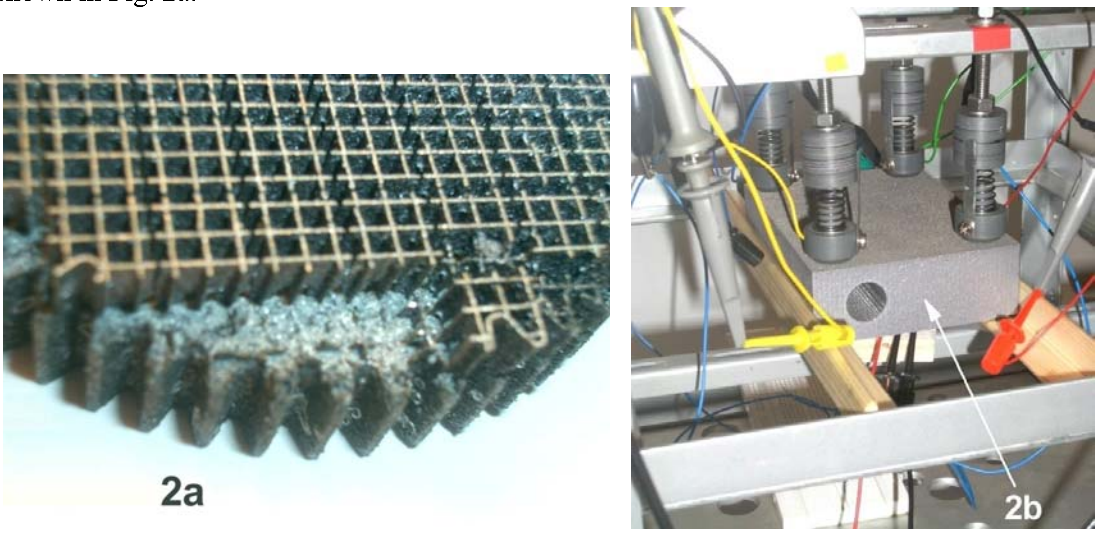

Fig. 2. a) Hollow mechanical elements manufactured by DLMS with collapsing cells, b) experimental set up of the QTUD method with the test AlSi12 sample.

Therefore, DLMS technology is still under development, with current work being focused on:

- improving the production process,
- improving the ability of numeric simulation,
- new methods of defectoscopy for quality control of final products.

A non-destructive defectoscopy method [11], although highly desirable, is unfortunately not possible [12]. The problem of ultrasonic defectoscopy dominated by the pulse echo technique is due to the use of very high frequencies (in the range of several GHz). Mechanical elements manufactured by laser sintering are often composed of cells ("honeycomb" structure) to achieve weight savings, therefore signals of the pulse echo technique experience huge absorption by the material. The cavity of the cells leads to collapse of ultrasound due to signal reflection within the cells.

The objective of this study is to present a concept developed for the improvement of the transmission ultrasonic defectoscopy method for materials using one ultrasonic head (for ultrasound emission) and four heads (for ultrasound reception), i.e. quadraphonic transmission ultrasound defectoscopy (QTUD). Four transmitted signals having passed through the test sample is received more or less weakened, i.e. with more or less delay, by the receiving ultrasonic heads (sensors), depending on the existence (especially of volume) of an enclosed defect. It aims to contribute to the development of science and technology, improving ultrasonic transmission method into an effective defectoscopy method for materials, especially porous materials. The main advantage of the QTUD method over previous ultrasound methods based on pulse echo methodology is the use of much lower frequencies (about a few tens of kHz, for example 45 kHz). Therefore, it can be successfully applied even on the extremely porous samples (e.g. various sintered polymers, sintered metals and indirectly and directly laser-sintered materials). The European patent application for the ultrasonic defectoscopy method described here has been filled at the „German Central Patent Office" [13].

2. Experimental

Fig. 2b shows the experimental set up of the QTUD method with the AlSi12 investigated sample. In presented measurements the operating frequency was 45 kHz. Measurements of ultrasound signal were made by a digital oscilloscope Owon PDS 5022S. Electronic solution to the QTUD method for materials testing has been already published elsewhere [14].

This AlSi12 sample was made by DLMS at the Fraunhofer Institute in Augsburg, Germany [15], using the SLM 250 HL devices (see the photo in Fig. 3. used by courtesy of the SLM Company [16]).

Fig. 3. SLM 250HL device of DLMS.

Grain size of the alloy powder ranged from 16 to 63 μm (by Gaussian distribution). Thickness of each individual layer was 50 μm and hardness is 105 HB. Power of the laser was 400 W; the gas used in the area was argon and melting temperature was 575 °C. The model used for scanning is shown in Fig. 1b.1, where the length of vector scanning can be represented as a sum of multiple scan of vectors widths. In this case the complete length of the samples was 120 mm and the scanning width matches the width of a cell wall. Duration of the method was 4 hours. The materials, i.e. such samples are used primarily for mechanical parts in space technology and in modern automotive engines technology.

The properties of the manufactured AlSi12 material were kindly provided by Fraunhofer Institute, Augsburg, and are given in Tab. I1.

Tab. I. Properties of AlSi12 material manufactured by direct laser metal sintering (DLMS) technology

Property	Value
Young's modulus	60 kN/m^2
Elongation boundary	270 N/m^2
Elongation hardness	340 kN/m^2
Endurance limits	2.7 %
Density	$1.09 \cdot 10^3$ kg/m^3

Fig. 4 shows an ultrasonic transmitter (S1) and four ultrasonic sensors (P1, P2, P3 and P4) positioned on the sample. S1 is positioned at the bottom of the sample, and P1, P2, P3 and P4, on the opposite, upper side of the sample. All ultrasonic heads were made from piezoelectric ceramic lead zirconium titanate crystal (PbZrTiO).

The investigated sample was 120 mm in length (L), 80mm in width (W) and 30 mm in height (H). Two built-in defects D_m and D_n were added to the sample in order to perform testing. The D_m defect is located near the P1 head in the form of cylinder having a diameter of 16 mm and depth of 45 mm. The D_n defect is located near the P4 head in the form of cylinder having a diameter of 8 mm and depth of 45 mm.

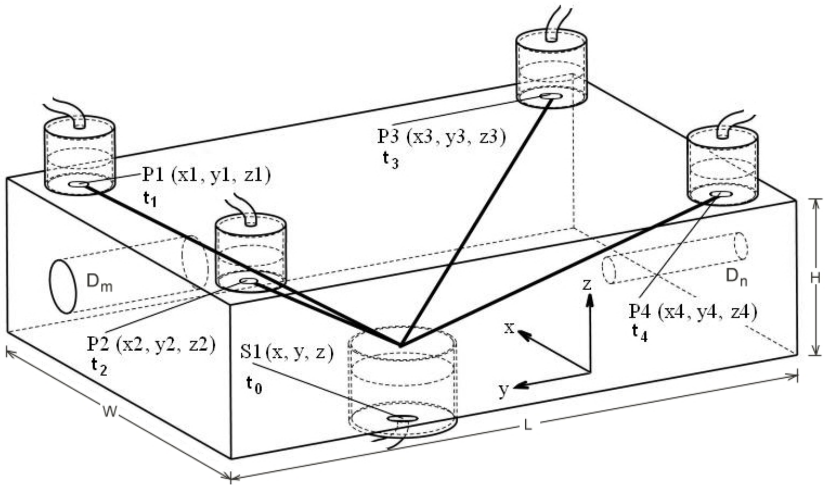

Fig. 4. Positions of ultrasonic heads on the test AlSi12 sample with built-in defects D_n and D_m.

Conclusions about the state inside the sample material can be derived from delay time of ultrasonic waves as well as from differences in the amplitudes received by the ultrasonic receiver heads.

The ultrasound head S1 (transmitter), emits an ultrasonic wave that passes through the sample. If the receiving ultrasound heads P1, P2, P3 and P4 are placed symmetrically to the transmitter S1 and if the structure of the tested sample is assumed not to contain any material defect, the ultrasonic waves emitted from S1 will arrive at the same time at any of the receiving heads P1, P2, P3 and P4. Furthermore, the signals received by P1, P2, P3 and P4 have the same amplitude.

If the investigated sample contains a material defect, the largest delay of ultrasonic signals will be at the ultrasonic head closest to the defect. The value of the delay is proportional to the speed of ultrasound through the material from which the sample was made. For a given material, this is a physical constant that must be already known in order to be able to perform the calculation.

The ability of the system to provide sufficient precision and register the delay of ultrasound signals substantially depends on the resolution of the analog digital converters used. It should be noted that the high-quality high resolution A/D converters are a significant investment.

If the sample contains a material defect, the attenuation of the ultrasonic signal amplitude is strongest in the ultrasonic head closest to the defect. This amplitude is really smaller than the other amplitudes and can be registered by relatively simple and cheap A/D converters.

The method presented here uses the amplitude attenuation principle in order to draw conclusions about the existence of defects within the investigated sample.

3. Results and discussion

The measurement was conducted on a sample containing embedded defects. The digital signals measured by a digital oscilloscope are shown in Fig. 5. During the measurement, the attenuation of amplitude of ultrasonic signal was recorded. The attenuation of the received amplitude is largest in the ultrasound receiver that is closest to the defect.

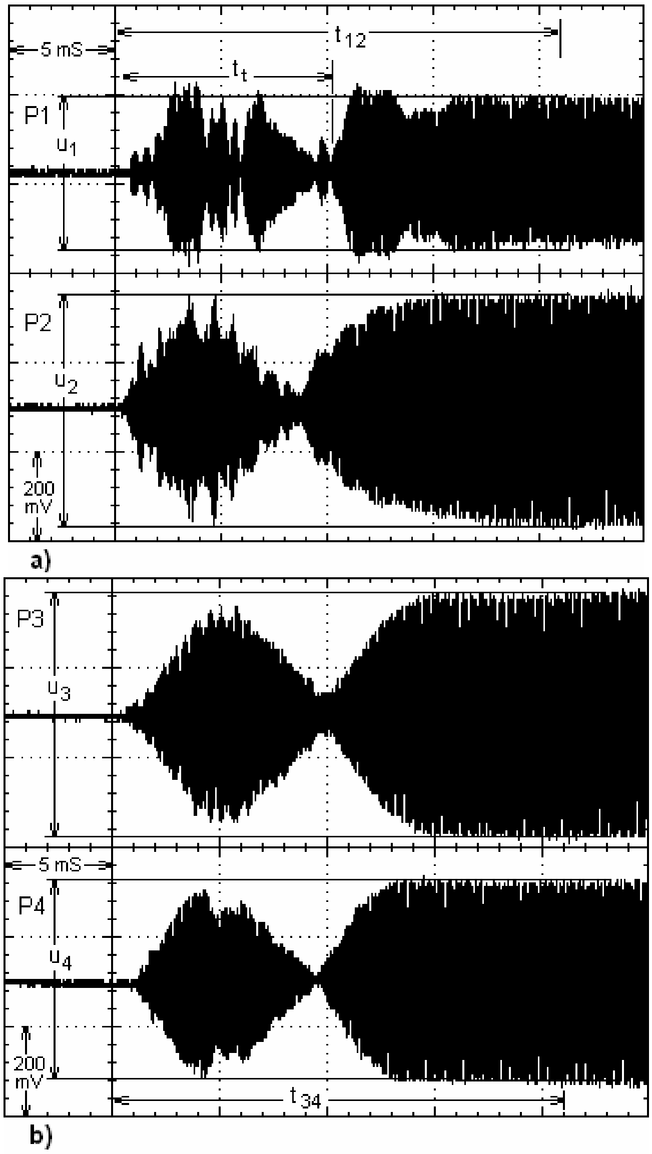

Fig. 5. Results of measurements from digital oscilloscope with built-in defects D_n and D_m:
a) recordings of the ultrasonic signal heads P1 and P2, defect D_m;
b) recordings of the ultrasonic signal heads P3 and P4, defect D_n.

Fig. 5a shows recordings of the ultrasonic signal heads P1 and P2. The upper part of the diagram corresponds to the recorded signal from the ultrasonic receiving head that is closest to the defect D_m (in this case, head P1, see Fig. 4), whereas the bottom part of the diagram shows the recorded signal of head P2. Voltage levels of u_1 and u_2 represent the particular maximums of the received amplitudes. Recognition of the persistently received amplitude is not automated. Therefore, due to lack of automation, the dimensions are graphically marked in the diagram.

Fig. 5a shows time t_{12}, which stands for the distance between voltages u_1 and u_2 on the horizontal time axis. This distance is characterized by time after which persisting voltages of receiving heads occur and voltage values are loaded for further calculations. After time t_{12}=22 ms, voltage u_1 stabilizes to 342 mV peak-to-peak, while voltage u_2 with permanently higher amplitude is 544 mV. Obviously, the difference between the amplitudes received from heads P1 and P2 is produced by the defect D_m.

Fig. 5b shows recordings of the ultrasonic signal heads P3 and P4. After time t_{34}=22 ms, voltage u_4 stabilizes to 465 mV peak-to-peak, while voltage u_3 with a permanently higher amplitude is 558 mV, similar to the voltage u_2. Therefore, the difference between the amplitudes received from heads P3 and P4 is caused by the defect D_n.

Fig. 6 shows the analysis of the received amplitudes at head P1 with and without defect for three different signal shapes (sinusoidal, square and triangle) with amplitude 15 V at transmitter S1. An important parameter used in the analysis was pressure of head over sample surface.

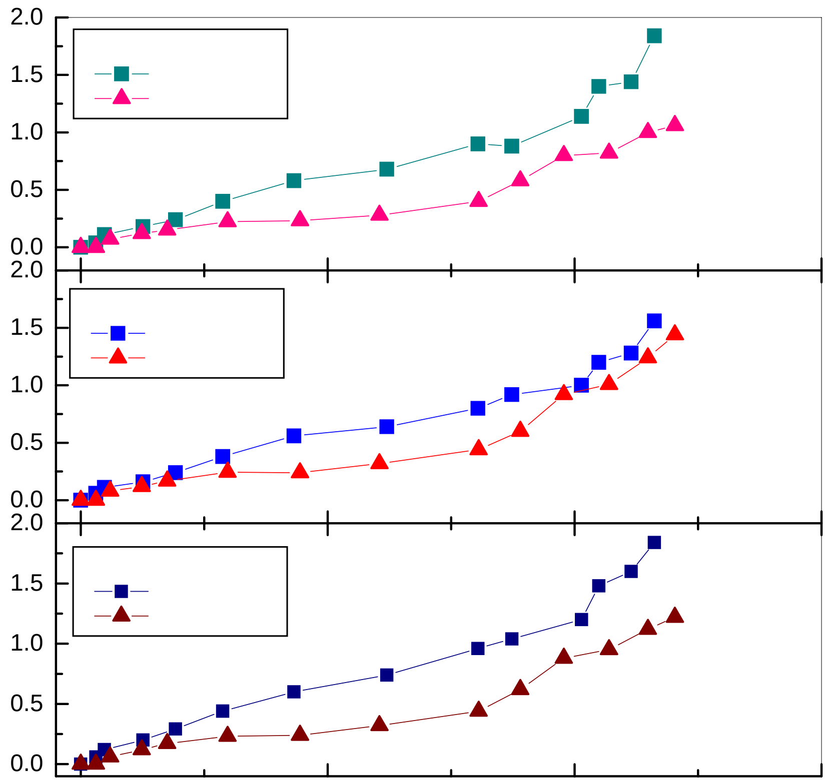

Fig. 6. Analysis of received amplitudes at sensor P1 with and without defect for sinusoidal, square and triangle wave.

Very similar signal levels are observed, but the difference of amplitudes is the lowest for the square signal wave. The optimum pressure of head over the sample surface is about 75 kN/m^2 where the highest difference of amplitudes was observed.

In order to obtain a series of measured values, further measurements using the pattern described above can be repeated for samples having the same dimensions but a different radius and depth of a built-in defect. Then, groups of data will enable the formation of tables to provide information about the existence of defects within the sample. As a next step, the samples with actual defects (occurring as a result of an error within the production cycle) can be investigated.

4. Conclusions

Compared to indirect laser metal sintering, direct laser metal sintering in is a more advanced procedure consisting of just one step in the process. Laser sintering has a range of advantages including an increase in the rate of manufacturing process, cost reduction, a high degree of automation and high precision of the product, customization of the product to individual needs, etc...

Ultrasonic defectoscopy is a scientific discipline that deals with finding errors i.e. defects in materials, especially in optically opaque materials that strongly absorb X-rays or in metals in which the use of electromagnetic signals is not possible due to the skin effect. The pulse echo method is currently the main "trend" in ultrasound defectoscopy, but the use of this method employing high frequencies (order of several GHz) causes excessive absorption of ultrasonic waves within a sample. Therefore, defectoscopy by means of the ultrasonic pulse echo method is not possible on very porous materials. The QTUD method presented in this paper comprises a single head as a transmitter and four ultrasonic sensors as the receivers at a low frequency of 45 kHz.

If the investigated sample contains material defect, the attenuation of the ultrasonic signal amplitude is strongest in the ultrasonic head closest to the defect. The observed amplitude is substantially lower than the other amplitudes and it can be recorded by relatively simple and cheap A/D converters.

In the present experimental procedure, the measurement was conducted on AlSi12 sample. The results obtained clearly show that there is excellent penetration through this material produced by direct laser metal sintering.

Acknowledgement

This paper reports work undertaken in the context of project OI 172057 financed by the Ministry of Education and Science of the Republic of Serbia.

References

1. M. Meindl, Beitrag zur Entwicklung generativer Fertigungsverfahren für das Rapid Manufacturing, Dissertation, Techinsche Universität München (2005).
2. A. Gebhardt, Generative Fertigungsverfahren. 3. Aufl. München: Hanser (2007).
3. J. Beaman, J. Barlow, D. Bourell, R. Crawfoed, Solid Freeform Fabrication. A New Direction in Rapid Manufacturing. Dordecht: Kluwer Academic Publishers (1997).
4. C. Deckard, Selective Laser Sintering, Dissertation, The University of Texas at Austin, USA (1988).
5. B. Badrinarayan, Study of the Selective Laser Sintering of Metal-Polymer Powders, Dissertation, The University of Texas at Austin, USA (1995).
6. J. Faehrer, Ganzheitliche Optimierung des indirekten Metall-Lasersinteringprozesses, Techinsche Universität München (2002).
7. C. Over, Generative Fertigung von Bauteilen aus Werkzeugstahl X38CrMoV5-1 und titan TiAl6V4 mit "Selective Laser Melting", RWTH Aachen (2003).

8. P. Bai, T. Li, "Study on High Temperature Sintering Processes of Selective Laser Sintered Al_2O_3/ZrO_2/TiC Ceramics", Science of Sintering, 41 (2009), 35-41.
9. S. Eshraghi, S. Das, "Mechanical and Microstructural Properties of Polycaprolactone Scaffolds with One-dimensional, Two-dimensional, and Three-dimensional Orthogonally Oriented Porous Architectures Produced by Selective Laser Sintering", Acta Biomaterialia, 6 (2010), 2467-2476.
10. L. Qin, J. Hu, C. Cui, H. Wang, Z. Guo, "Effect of Al Content on Reaction Laser Sintering of Ni-Al Powder", Science of Sintering, 40 (2008), 295-301.
11. G. Sorge, Faszination Ultraschall, Teubner Verlag Stuttgart (2002).
12. H. Kuttruff, Physik und Technik des Ultraschalls, Hirtzel Verlag Stuttgart (1988).
13. "Deutsches Patent- und Markenamt" ("DPMA") ("German Central Patent Office") Berlin, Germany.
14. Z. Ebersold, N. Mitrović, S. Djukić, Electronics, 15 (2011), 61-66.
15. Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e. V., München, Germany; Fraunhofer-Institut Augsburg, Germany, http://www.fraunhofer.de
16. SLM Solutions GmbH, Lübeck Germany, http://www.slm-solutions.com

---

Садржај: *У раду су приказана побољшања дефектоскопије ултразвуком машинских делова произведених директним ласерским синтеровањем метала. Код поступка директног ласерског синтеровања метала, довођење мешавине металног праха и накнадно учвршћавање ласером, изводи се у једном јединим процесном кораку. Машински делови произведени ласерским синтеровањем често су саздани од шупљих ћелија како би се добили што лакши делови. Над таквим узорцима, распрострањена ултразвучна импулсна ехо метода, са својим високим фреквенцијама од неколико гигахерца, није успешна. Циљ овог рада је приказ квадрофонске трансмисионе ултразвучне дефектоскопије која користи много ниже фреквенције, од неколико десетина килохерца. На основу тога је могућа и дефектоскопија и код шупљикавих материјала произведених директним ласерским синтеровањем. У овом раду су приказани резултати истраживања на узорку од AlSi12 произведеном на Фраунхофер институту у Аугсбургу, Немачка.*
Кључне речи: *Директни поступак ласерског синтеровања метала; AlSi12, ултразвучна дефектоскопија; квадрофонска трансмисиона ултразвучна дефектоскопија.*
