Aluminium alloy addition effects on the behaviour of soft magnetic materials at low frequencies

ALUMINIUM ALLOY ADDITION EFFECTS ON THE BEHAVIOUR OF SOFT MAGNETIC MATERIALS AT LOW FREQUENCIES

Róbert Bidulský[1)], Jana Bidulská[1)], Marco Actis Grande[2)], Luca Ferraris[3)]*
[1)]Technical University of Košice, Faculty of Metallurgy, Košice, Slovakia
[2)]Politecnico di Torino, Department of Applied Science and Technology, Torino, Italy
[3)]Politecnico di Torino, Department of Energy, Torino, Italy

Received: 04.07.2014
Accepted: 01.08.2014

[*]Corresponding author: e-mail: robert.bidulsky@tuke.sk, Tel.: +421 055 602 4124, Department of Metal Forming, Faculty of Metallurgy, Technical University of Košice, Letná 9, 042 00 Košice, Slovakia

Abstract
The present paper focused on the effects of aluminium alloy addition on the behaviour of soft magnetic materials at low frequencies. The microstructure investigation reveals that for materials with high aluminium contents, the pores are oriented near or surrounding the aluminium particles. The microstructure investigation reveals that for materials with high aluminium contents, the pores are oriented near or surrounding the aluminium particles, as well as after heat treatment shows coarse-grained structure with a minimum number of inclusions within the grains and at the grain boundaries. Results show that the magnetic properties are dependent on the structural state of the investigated material. Magnetic properties increased with decreasing density due to the enhanced densification by means of applied pressing pressure and promote porosity reduction during heat treatment.

Keywords: Soft magnetic materials, Insulated iron powder compound, Aluminium alloy, Coercivity, Specific losses

1 Introduction

Iron based Soft magnetic materials (SMM) are a relatively new material in electromagnetic application. SMM consist of heat-treated powder compacts (no sintered) formed by pure iron powder particles coated with a very thin electrically insulated (on polymer base) layer. These materials have become increasingly popular during the last years due to their several advantages, such as reduction in weight and size. Additionally, insulated iron powder compound (IIPC) offers several advantages over traditional laminated steel due to the isotropic nature of the IIPC combined with the unique shaping possibilities opens up for 3D-design solutions [1-8].
A summary of the advantages of IIPC parts include [9-14]: the ability to produce complex shapes to net shape without waste of material and the ability to tailor the magnetic properties to a specific application by controlling the material and the processing parameters. IIPC cannot be sintered as it is fundamental that each particle is electrically insulated from the other one. Nevertheless, since during compaction a stress is introduced in the particles, which deteriorates the soft magnetic properties, heat treatment has to be settled to provide a stress relief. Magnetic properties of the IIPC are influenced by the amount and type of coating layer (covered the iron

DOI 10.12776/ams.v20i3.351 p-ISSN 1335-1532
e-ISSN 1338-1156

particle) and the particle size distribution of the iron powder. Insulated iron powder composites are used in the as compacted and heat treated condition and usually exhibit low eddy current losses. Applications for these materials are AC magnetic devices that require the minimization of eddy current losses. One drawback of the iron powder polymer composites is the high coercive force. This high coercive force increases the hysteresis losses dramatically, resulting in reduced magnetic performance at low frequencies.

Therefore, the main aim of the presenting paper is to find proper electromagnetic properties usage in low-frequency applications at 50 Hz, considering the trend towards a more widespread use of automotive electric systems in motors. These applications require high density (secondary operations are needed) for magnetic properties and precision. On the other hand, the secondary operations degrade magnetic properties, and strength are weak.

2 Experimental conditions

The IIPC material (Somaloy powder, Hoganas AB) has been admixed with different amounts of aluminium alloy (ALUMIX 321, Ecka Granules). Chemical composition of aluminium alloy is given in the following **Table 1**.

Table 1 Chemical composition of the alloy added to the base powder

Al	**lubricant**	**Cu**	**Mg**	**Si**	**Fe**
Balance	1,50	0,21	0,95	0,49	0,07

The specific results reported in this work take into account the use of aluminium alloy 321 added in the amount of 0, 5 and 10 % in weight to the base IIPC powder. Powder mixtures were homogenized using a laboratory Turbula mixer for 20 minutes. Specimens with a different green density obtained using a 2000 kN hydraulic press, in a disc-shaped mould (Φ 40 mm) and unnotched impact energy 55×10×10 mm^3 specimens applying a pressure in the range from 400 to 800 MPa. Different thermal treatments (in air, means (a) and in nitrogen(means (b)) were carried out on the evaluated systems, all implying a step at the maximum temperature of 500°C for 30 min. Densities were evaluated using the water displacement method, according to the ASTM B962 – 08 standard. The compositions are given in the following **Table 2**.

Table 2 Chemical composition of the alloy added to the base powder

No.	**Composition**
1	IIPC
2	IIPC+5 % Al321
3	IIPC+10 % Al321

Magnetic tests system realization and samples characterization have equipped with two windings: the first one to produce magnetization in the core with appropriate m.m.f., the second one to pick up the magnetic induction.

3 Results

The representative microstructures of investigated materials are presented in **Figs. 1-6**.

DOI 10.12776/ams.v20i3.351 p-ISSN 1335-1532
e-ISSN 1338-1156

Microstructure in the pressed state reveals, that pores act as crack initiators and due to their presence the distribution of stress is inhomogeneous across the cross section and leads to the reduction of the effective load bearing area.

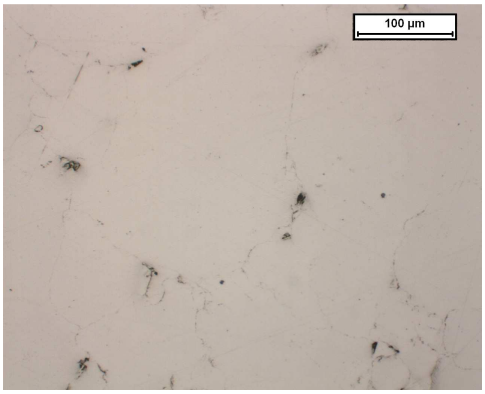

Fig. 1 Microstructure of material 1a

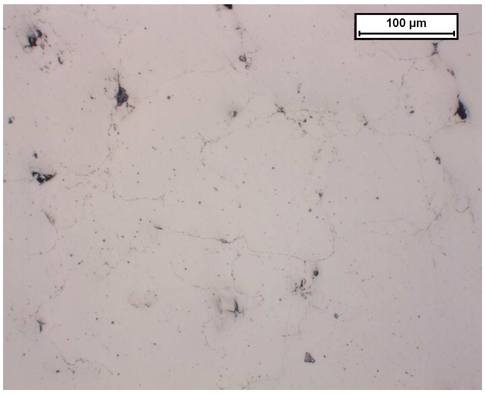

Fig. 2 Microstructure of material 1b

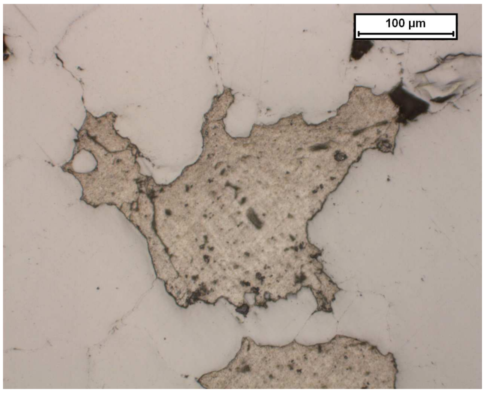

Fig. 3 Microstructure of material 2a

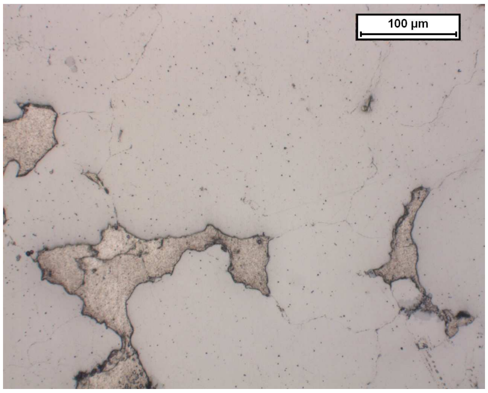

Fig. 4 Microstructure of material 2b

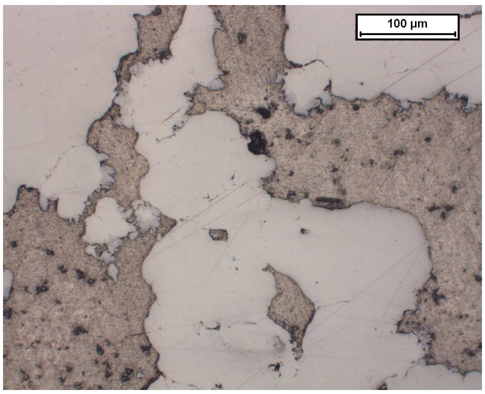

Fig. 5 Microstructure of material 3a

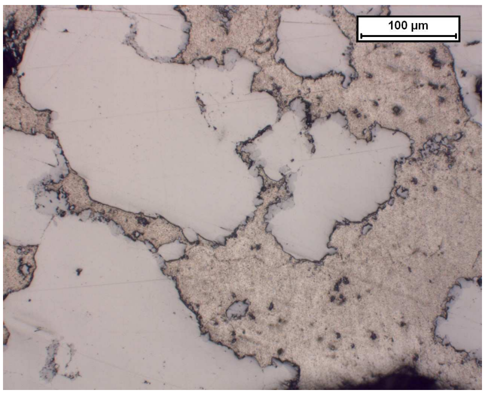

Fig. 6 Microstructure of material 3b

DOI 10.12776/ams.v20i3.351 p-ISSN 1335-1532
e-ISSN 1338-1156

In the microstructure in both processing, condition are presented pores as black point. For materials with high aluminium contents, the pores are oriented near or surrounding the aluminium particles. The deeper investigation about porosity phenomena, mainly with respect to powder metallurgy aluminium alloys are presented in [15-18]. Heat treatment regime results in a coarse-grained structure with a minimum number of inclusions within the grains and at the grain boundaries. It is well-known that the porosity has a negative effect on the magnetic properties such as the magnetic induction and permeability as well the coercive force, which their influence are decreasing and increasing, respectively. Comparison of the results indicates that the magnetic properties are considerably dependent on the structural state of the alloy. More authors [13, 19-23] underline that the behaviour of powders during the pressing process and heat treatment is important question in the improving of SMM to give a suitable combination between pressing pressure, heat treating regime as well as magnetic properties.
The typical B-H magnetization behaviour for investigated materials in both processing conditions are presented **Figs. 7-12**.

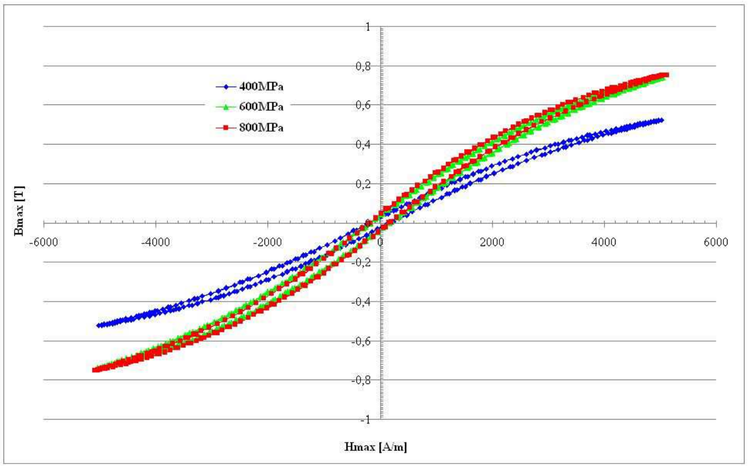

Fig. 7 B-H curves at 50 Hz of the material 1 treated in air

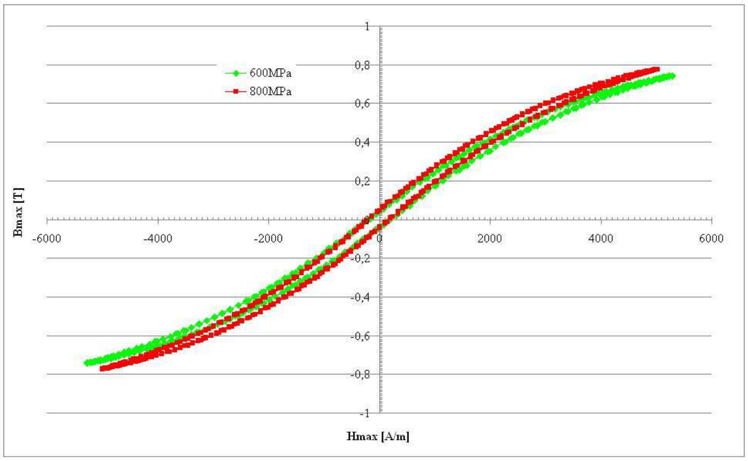

Fig. 8 B-H curves at 50 Hz of the material 1 treated in nitrogen

DOI 10.12776/ams.v20i3.351 p-ISSN 1335-1532
e-ISSN 1338-1156

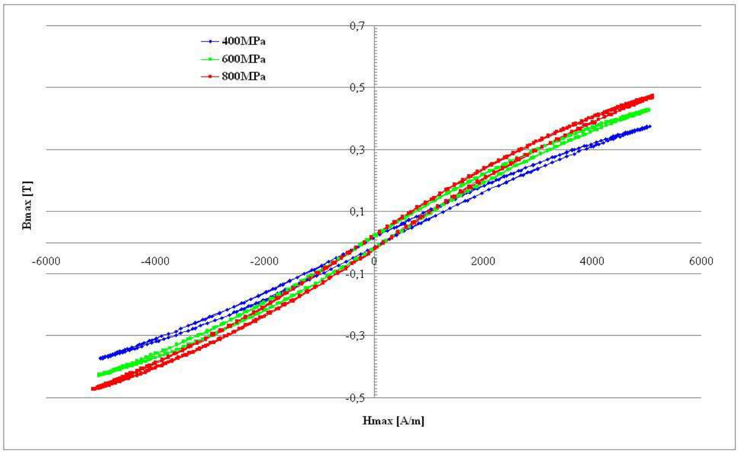

Fig. 9 B-H curves at 50 Hz of the material 2 treated in air

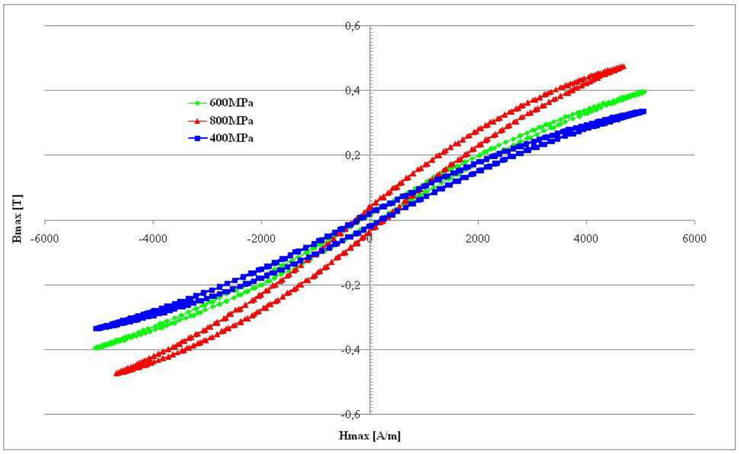

Fig. 10 B-H curves at 50 Hz of the material 2 treated in nitrogen

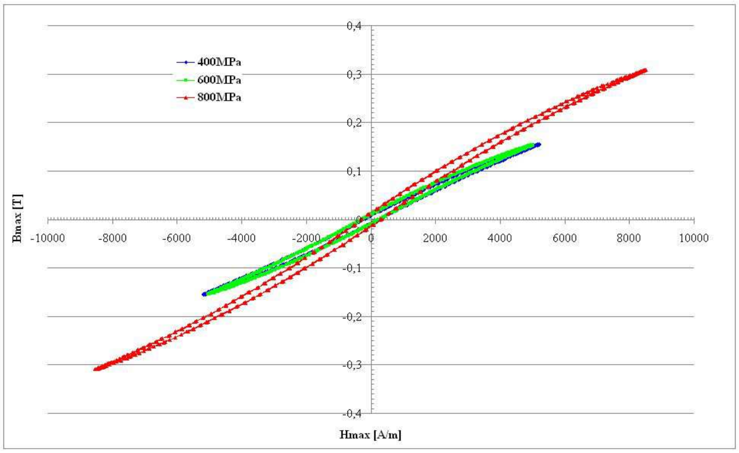

Fig. 11 B-H curves at 50 Hz of the material 3 treated in air

DOI 10.12776/ams.v20i3.351 p-ISSN 1335-1532
e-ISSN 1338-1156

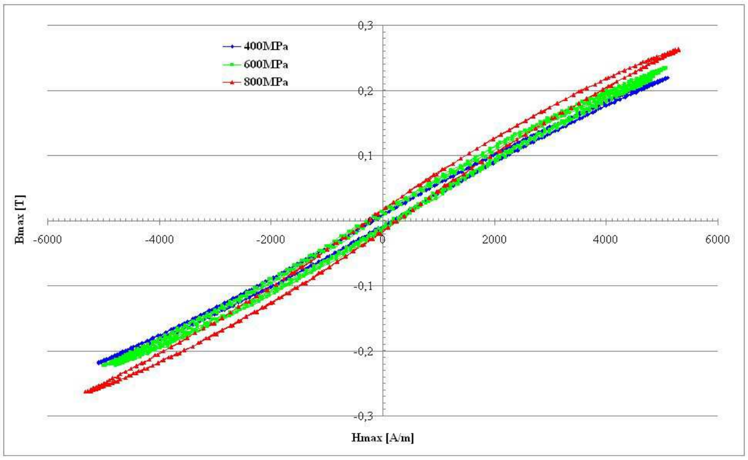

Fig. 12 B-H curves at 50 Hz of the material 3 treated in nitrogen

4 Discussion

The ideal soft magnetic material, with respect to IIPC, is an isotropic media with very high magnetic permeability, low coercivity and high saturation induction. In addition, the material could be easily shaped into 3D structures in order to fully take advantage of the material's isotropic nature [1]. In the manufacture of SMM components during the compaction step, plastic deformation of the particles that takes place, results in higher hysteresis losses. It is clear that new idea of compaction processes are needed being explored that could eliminate the hardening of the iron powder due to maximizing energy efficiency should minimize core loss, mainly hysteresis loss that increases due to stresses introduced in the material at compaction.

Due to the fact, as underlined in the past activity [4-13], that a maximum temperature of 500°C is compatible with the conservation of good magnetic properties of IIPC, the attention has been devoted to select a material able to introduce mechanical advantages under heat treatment at the reported temperature. As a consequence, the attention has been addressed to the aluminium, which at 500°C presents a sort of pre-sintering behaviour (in the case of the IIPC components made of metal powder cannot obviously be sintered because each particle has to be electrically insulated from the others), with the possibility of a fluid migration around the IIPC grains, and good rigidity after the cooling process. The production of a mixture of different powders; typical soft magnetic powders represent by IIPC and Aluminium alloy 321 as a possible additional element, which are responsible for the more homogeneous microstructure and as a better plastically ability agent than matrix powder one. Despite of the densification phenomena of aluminium alloy addition [24, 26] some additional research and focused on the densification behaviour is needed.

The summary of magnetic properties is given in the **Fig. 13**.

The present **Fig. 13** show that the magnetic properties are really satisfying the requirements of producers; despite of fact that in investigated microstructures some discontinuities occur, such as interconnected and residual porosity.

Additionally, the ideal result should be the realization of a kind of spatial cage around the single insulated magnetic grains adding mechanical resistance without losing too much of the magnetic properties.

DOI 10.12776/ams.v20i3.351 p-ISSN 1335-1532
e-ISSN 1338-1156

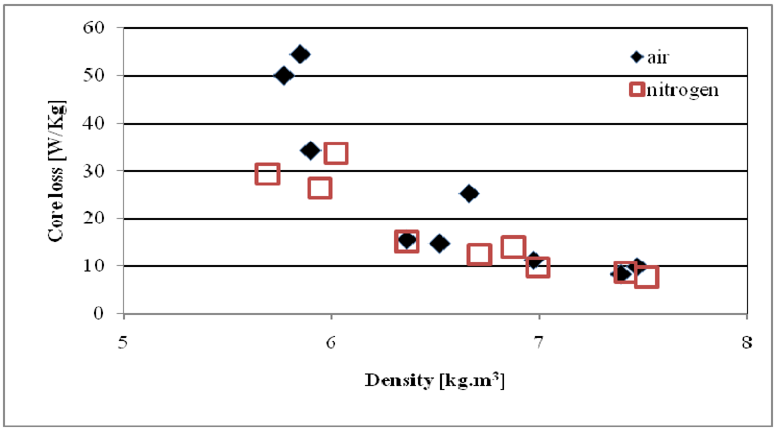

Fig. 13 The summary of magnetic properties

5 Conclusions

The results show that:

1. The microstructure investigation reveals that for materials with high aluminium contents, the pores are oriented near or surrounding the aluminium particles, as well as after heat treatment shows coarse-grained structure with a minimum number of inclusions within the grains and at the grain boundaries.
2. Magneric properties increased with decreasing density due to the enhanced densification by means of applied pressing pressure and promote porosity reduction during heat treatment.

References

[1] H. Shokrollahi, K. Janghorban: Journal of Materials Processing Technology, Vol. 189, 2007, p. 1-12, DOI: 10.1016/j.jmatprotec.2007.02.034
[2] J. Ma et al.: Powder Technology, Vol. 253, 2014, p. 158-162, DOI: 10.1016/j.powtec.2013.11.011
[3] E. Bayramli, O. Olgelioglu, H.B. Ertan: Journal of Materials Processing Technology, Vol. 161, 2005, p. 83-88, DOI: 10.1016/j.jmatprotec.2004.07.070
[4] L.O. Hultman, O. Andersson, A.G. Jack: The SMC Technology - From Idea to Reality. SAE Technical Paper 2003-01-0449, 2003, doi:10.4271/2003-01-0449.
[5] J. Ma et al.: Materials and Design, Vol. 51, 2013, p. 1018-1022, DOI: 10.1016/j.matdes.2013.05.017
[6] P. Jansson: *SMC Materials – Including Present and Future Applications*. In: Advances in Powder Metallurgy and Particulate Materials (PM^2TEC 2000), MPIF, 2000, p. 87-97
[7] K. Asaka, C. Ishihara: Hitachi Powdered Metals Technical Report, Vol. 4, 2005, p. 3-9
[8] R. Bidulský, M. Actis Grande, L. Ferraris, P. Ferraris, J. Bidulská: Acta Physica Polonica A, Vol. 118, 2010, p. 802-803
[1] R. Bidulský, J. Bidulská, M. Actis Grande: Archives of Metallurgy and Materials, Vol. 58, 2013, No. 2, p. 365-370, DOI: 10.2478/amm-2013-0001
[9] R. Guo, C. Cheng, J. Lee: *Developing a Soft Magnetic P/M Component used in Wireless Communication Devices with High Green Strength Lubricants*. In: Advances in Powder Metallurgy and Particulate Materials, MPIF, Vol. 14, 2002, p. 73-78

DOI 10.12776/ams.v20i3.351
p-ISSN 1335-1532
e-ISSN 1338-1156

[2] I.P. Gilbert, V. Moorthy, S.J. Bull, J.T. Evans, A.G. Jack: Journal of Magnetism and Magnetic Materials, Vol. 242-245, 2002, p. 232-234, DOI: 10.1016/S0304-8853(01)01252-5
[3] C. Lall: The Effect of Sintering Temperature and Atmosphere on the Soft Magnetic Properties of P/M Materials. In: *Advances in Powder Metallurgy and Particulate Materials*, Vol. 3, 1992, p. 129-138
[4] H. Shokrollahi, K. Janghorban: Materials Science and Engineering B, Vol. 134, 2006, p. 41-43, DOI: 10.1016/j.mseb.2006.07.015
[5] E. Enescu, P. Lungu, S. Marinescu, P. Dragoi: Journal of Optoelectronics and Advanced Materials, Vol. 8, 2006, p. 745-748
[10] J.M. Martín, B. Navarcorena, I. Arribas, T. Gómez-Acebo, F. Castro: *Dimensional Changes and Secondary Porosity in Liquid Phase Sintered Al Alloys*. In: Euro Powder Metallurgy Congress, EPMA, Shrewsbury, Vol. 4, 2004, p. 46-53
[11] R. Bidulský, J. Bidulská, M. Actis Grande: High Temperature Materials and Processes, Vol. 28, 2009, p. 337-342
[12] J. Bidulská et al.: Acta Metallurgica Slovaca, Vol. 16, 2010, No. 1, p. 4-11
[13] J. Bidulská et al.: Acta Physica Polonica A, Vol. 122, 2012, No. 3, p. 553-556
[14] S. Kikuchi, D. Koyama, K. Nakamura: *A design of ultrasonic compaction tools for metal powder magnetic core of motors.* In: Ultrasonics Symposium (IUS 2008), 2008, p. 2142-2145, DOI: 10.1109/ULTSYM.2008.0530
[15] I. Gilbert et al.: Journal of Materials Science, Vol. 39, 2004, p. 457-461, DOI: 10.1023/B:JMSC.0000011498.90378.7e
[16] R. Bidulský, M. Actis Grande, L. Ferraris, J. Bidulská: Journal of Optoelectronics and Advanced Materials, Vol. 12, 2010, p. 1356-1359
[17] J. Bidulská, T. Kvačkaj, R. Bidulský, M. Actis Grande, L. Ferraris: Acta Physica Polonica A, Vol. 118, 2010, p. 800-801
[18] M. Actis Grande, R. Bidulský, A. Cavagnino, L. Ferraris, P. Ferraris: IEEE Transactions on Industry Applications, Vol. 48, 2012, No. 4, p. 1335-1343, DOI: 10.1109/TIA.2012.2199951
[19] J. Bidulská, T. Kvačkaj, I. Pokorny, R. Bidulský, M. Actis Grande: Archives of Metallurgy and Materials, Vol. 58, 2013, No. 2, p. 371-375, DOI: 10.2478/amm-2013-0002
[20] J. Bidulská et al.: Chemicke Listy, Vol. 105, 2011, No. 16, p. s471-s473
[21] J. Bidulská, R. Bidulský, T. Kvačkaj, M. Actis Grande: Steel Research International, Vol. SI, 2012, p. 1191-1194

Acknowledgements
This work was realized within the frame of the Operational Program Research and Development: "The centre of competence for industrial research and development in the field of light metals and composites", project code ITMS: 26220220154 and financially supported by a European Regional Development Fund.