EFFECT OF POWDER SIZE AND FOAMING AGENT ON ALUMINIUM FOAM EXPANSION

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Abstract

Aluminium foam is an isotropic highly porous metallic material with a cellular structure. To prepare the stabile foam it is necessary to use, except foaming agent, also others additives that stabilize forming of cell walls and avoid to their collapse [1, 2]. For manufacturing of complex shaped aluminium foam parts the most suitable method is based on the foaming of precursors. Precursor is the compacted mixture of aluminium alloy powder and suitable foaming agent. For this reason this method of preparation is called *powder metallurgy route* [3]. Disadvantage of this process is the relatively high price of final good. The motivation is to develop the cheap method for the manufacturing of aluminium foam direct from melt. The main idea is to admix homogenously aluminium foam oxides to create stable aluminium foam. Source of the oxides will be surface of Al- powders contained in foamable precursor. The oxide content was varied in the form of size and shape of used aluminium powder. The foam kinetics was evaluated in so called *"expandometer"*. Samples are prepared from AlMgSi0.6 alloy with by TiH_2 as a blowing agent [4].

INTRODUCTION

Metallic foams are relatively unknown structural materials, however with enormous future potential for applications where lightweight combined with high stiffness and acceptable manufacturing costs are of prime interest. Aluminium foam is an isotropic highly porous metallic material with a cellular structure. The essentially spherical and closed pores occupy more than 70% of the total volume. Mechanical and physical properties depend strongly on the density which lies typically in the range of 0.4- 1.2 g. cm^{-3}. Aluminium foam prepared by powder metallurgical method is very efficient in sound absorption, electromagnetic shielding, impact energy absorption, vibration damping and it is non-flammable. Foamed aluminium is form-stable also at elevated temperatures. Aluminium foam is recyclable and thus environmentally friendly. For future industrial applications it offers the combination of apparently concurrent properties in one homogeneous material, thus saving material, energy and environment [3].

There are two basic preparation methods:
- **Melt route**: mixing of foaming agent (metal hydride, e.g. TiH_2) into a molten aluminium or aluminium alloy. The foaming agent decomposes at the melting temperature of aluminium, releases gas (e.g. hydrogen) and blows up the melt

- **Powder metallurgical (PM) route**: heating of gas-tight precompacted mixture (precursor) of aluminium or aluminium alloy powder with powdered foaming agent above the melting point of the metallic matrix; the foaming agent decomposes and expands the precursor into porous cellular solid.

Various techniques based on both principal methods have been investigated to achieve the uniform cellular structure of the foam at reasonable costs. MEPURA and our Institute have developed the cost effective method which involves a foaming up of the powder-based foamable precursor in the desired hollow mould to achieve required (also complicated) shapes. The main benefit of this method is the possibility to use the same foaming material of simple geometry (e.g. wire, rods, balls, etc.) for different shapes to be foamed. Using this method diverse parts made from foamed aluminium (flat-, rod-, or 3D-shapes), as well as integral foams can be produced; i.e. foams connected with bulk metal sheets (e.g. sandwich structures), or hollow metallic profiles filled with the foamed aluminium [5].

PM techniques comprise foaming of the precursor prepared by compacting of powdered metal or alloy, whereas the pore forming gas is developed during melting of this precursor from admixed foaming agent. The powder must be thoroughly compacted in order to seal the particles of foaming agent. This avoids the premature release of the gas at heating. The formation of the pores starts during the melting of the metal matrix. If the precursor is inserted in a suitable mould before foaming, the foam follows its shape. Subsequent rapid solidification produces final shaped component with a continuous surface skin and a cellular internal structure. PM foams can be prepared with gradient pore size and also with preferred orientation of pores. The possibility to use the simple-form precursor e.g. extruded rods or ribbons for foaming of components with various shapes and sizes lowers the high production costs, which represented the main disadvantage of PM process.

PM foams are always covered by dense skin, which significantly improves the mechanical properties (e.g. bending stiffness, etc.). However the natural skin of foams has variable thickness and sometimes contains small holes or cracks. These inevitable defects can initiate premature fracture of the foam, especially when they appear on the tensile loaded surface of foamed part. Reinforcing of tensile loaded surface skin with metallic or ceramic wires woven into grids with various mesh size can solve this problem very efficiently. According to a novel foaming technique developed recently, the reinforcements are placed in the foaming mould together with foamable precursor and the foam expansion moves them to the mould surface where they are infiltrated with molten cell-wall material. The main advantages of this method are its simplicity, lower manufacturing costs and the possibility to reinforce the foamed part selectively and anisotropicaly according to the applied load [6].

PREPARATION OF MATERIALS

The PM process consists of mixing metal powder and a powdered blowing agent, compacting the mix to a dense semi- finished product (called „*foamable precursor material*") by hot pressing, extrusion, powder rolling or other methods. In a final step the foamable precursor material is expanded by heating it above melting point of its matrix metal. This transfers the metal into a semi- liquid viscous state and simultaneously makes the blowing agent decompose, thus releasing gas and creating a highly porous structure [7].

To investigate the effect of aluminium oxide content four mixtures of aluminium and aluminium alloy powders were prepared as foamable precursors by PM route. The compound and size of powders is shown at table 1. TiH_2 powder was used as obtained and thermally treated at 450ºC for 1 hour (denoted as Chemmetal).

COMPOSITION OF FOUR AlMg1Si0.6 POWDER MIXTURES:
VARIOUS ALUMINIUM AND TiH₂ POWDER SIZE   Table 1

	Al [79 wt.%]	AlMg5 [wt.%]	Si [wt.%]	TiH₂ [0.4 wt.%]
A	<200 μm			<63 μm
B	< 200 μm	20	0,6	Chemmetal⁺
C	< 400 μm			<63 μm
D	< 400 μm			Chemmetal⁺

+ coarse powder already used for large scale aluminium foam production, thermally treated

EXPERIMENTAL PROCEDURE

Foaming tests were performed by foaming of the precursor tablets inside so-called expandometer equipment. Expandometer measures immediate height of foam expansion. The equipment enables to control foaming temperature and time (control over heating rate). It makes possible to appreciate cell wall stability via measuring of foam collapse. The metal foam is created inside a small cylindrical steel mould, which is open only at the top. The mould is located in the centre of a glass tube where it is held by a sample support made of stainless steel. Mould is heated by infra red lamps placed around behind glass tube. From the top is placed movable piston made of stainless steel, which record height of expansion. Thermo junctions record temperature from the bottom and from the top of the sample and also measure temperature of the mould.

For the foaming tests a cylindrical piece of a foamable precursor material was placed inside the steel mould and was then heated under desired conditions above melting point of used aluminium alloy. Geometry, number of samples and heating rate of samples for each mixture were the same and are given in table 2. Before foaming, the average densities of tablets were measured and their was calculated porosity with respect to dense aluminium (2.7 g.cm⁻³) – see Table 3.

GEOMETRY, HEATING RATE AND NUMBER
OF SAMPLES   Table 2

Diameter [mm]	Height [mm]	heating rate [°C/s]	Number of samples
19	5	1	5

DENSITIES AND POROSITY OF PRECURSORS
TABLETS USED IN EXPERIMENT   Table 3

Average values	Density [g.cm⁻³]	Porosity [%]
A	2.678	0.816
B	2.638	2.312
C	2.657	1.589
D	2.674	0.955

RESULT AND DISCUSSION

As foam growth is a statistical process, two foaming experiments will never yield exactly the same result. Accidental agglomerates of blowing agent particles in foamable

precursor or unpredictable heat transfer between the heat source and the foamable precursor samples are possible sources for this irreproducibility. Moreover, the experimental equipment might contain elements which limit reproducibility of foaming experiments, e.g. friction effects between molten foam and mould are hardly reproducible.

The obtained results (see Fig.1) can be summarised as follows: data sets show the stages of foam formation, namely:

- below the solidus temperature of the aluminium alloy the expansion is small and linear
- when the solidus temperature of the aluminium alloy is reached, it starts to soften and expands slowly as a consequence of the decomposition of TiH_2 to H_2 gas and Ti
- as the temperature increases, the expansion rate increases rapidly until the maximum expansion is reached,
- finally the blowing agent is exhausted and no longer releases hydrogen and the foam starts to collapse.
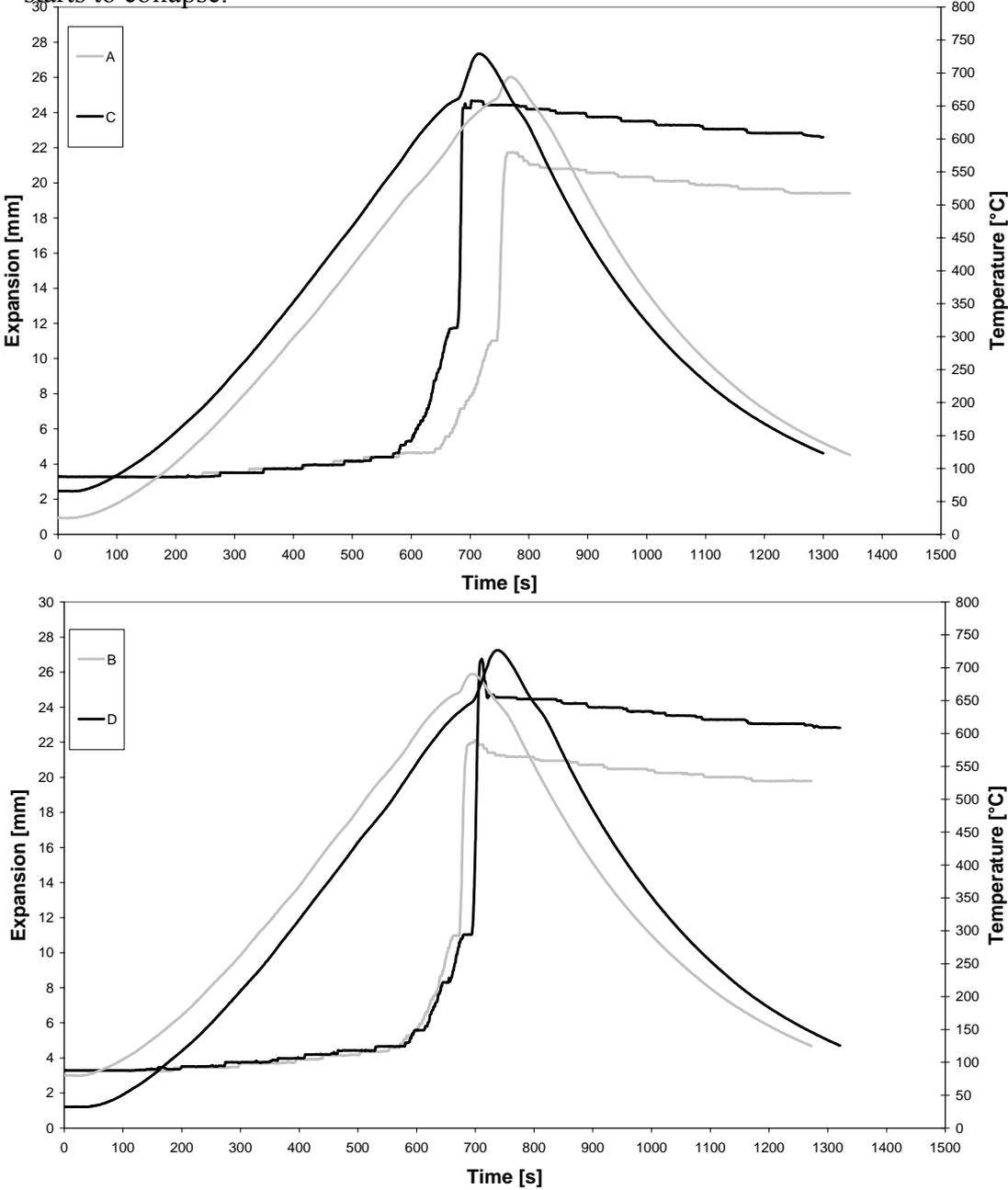
Fig. 1. *Typical output results from expandometer- expansion in dependence on time and temperature for the investigated precursor materials: up – as received TiH₂, down – heat treated TiH₂*

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Table 4 shows values of expansion and temperature measured at the bottom of sample for four investigated precursors at different stages of foam expansion. As can be seen the values are very scattered even for the same composition. This may be caused by dissimilar conditions of experiment. To simplify this, we are considering the average values for each mixture.

The experiments indicate, that the heat treatment of foaming agent leads to a bit smaller maximal expansion of foam made from precursor containing heat treated foaming agent (see Table 5). During heating up to and during the dwell on the temperature of heat treatment (450ºC in this case) some amount of hydrogen gas is already evolved from the foaming agent. This evolved gas is missing during foaming thus leading to smaller foam expansion. On the other hand (see Fig. 2) it leads to a bit more homogeneous structure of final foam. The more homogeneous structure is due to pores of almost the same size in foam: As evolved gas does not fill pores and cracks before the solidus temperature is reached, gas bubbles within molten aluminium alloy start to create almost at the time. In the case of as received foaming agent the gas within pores and cracks creates very early some amount of bubbles. Then new created small bubbles tend to coalescence with already created larger bubbles thus creating even large bubbles. This is inevitable from the point of view of foam stability and foam mechanical properties.

Precursors made from small powder (< 200 μm) showed significantly smaller maximal expansion of foam as precursors made from bigger powder (< 400 μm) for both as received and heat treated foaming agent powders. This is surprisingly, as smaller powders will have higher surface area and therefore also higher oxides contents in comparison with bigger powders. Moreover the both powders are almost of the same shape (see Fig. 3). The most probably, space distribution of foaming agent powders play an important role in this case. The results will be studied more precisely also for other aluminium alloy powders composition. On the other hand, the collapse of foam made from all precursors is almost the same and is about 9 – 10 % of maximal foam expansion.

VALUES OF EXPANSION AND T BOTTOM AT SPECIFIC STAGES   Table 4

	Start of test		Start of expansion			Maximum of expansion			Maximum of T bottom			End	
	Expansion [mm]	Tbottom [°C]	Time [s]	Expansion [mm]	Tbottom [°C]	Time [s]	Expansion [mm]	Tbottom [°C]	Time [s]	Expansion [mm]	Tbottom [°C]	Time [s]	Expansion [mm]
	3.29	60	571	4.49	552	770	22.87	684	764	22.7	686.17	1250	16.28
	3.29	25	635	4.65	554	625	23.02	642	643	23.02	662.66	1345	19.42
	3.28	71	568	4.42	549	720	17.64	659	701	16.74	671.66	1275	18.69
	3.26	25	648	5.12	569	772	21.74	693	770	21.72	693.93	1340	21.04
	3.27	74	530	4.62	545	712	20.31	674	703	20.08	678.97	1222	20.11
A	**3.28**	**50.99**	**590.4**	**4.66**	**553.93**	**719.8**	**21.116**	**670.6**	**716.2**	**20.85**	**678.7**	**1286.4**	**19.11**
	3.28	77	560	4.22	556	504	21.03	693	507	21.02	693.1	1292	21.67
	3.28	60	568	4.43	546	750	20.24	662	731	19.85	675.68	1281	16.71
	3.28	80	562	4.59	554	694	24.44	730	707	24.21	744.23	1272	19.79
	3.3	253	391	4.87	580	725	18.29	665	709	17.84	675.37	1076	18.05
	3.28	33	596	4.6	547	701	22.09	689	695	21.97	690.6	1306	18.69
B	**3.28**	**101.01**	**535.4**	**4.54**	**556.36**	**674.8**	**21.218**	**687.8**	**669.8**	**20.98**	**695.8**	**1245.4**	**18.98**
	3.28	67	566	4.43	541	685	24.08	685	710	22.13	733.64	1306	25.78
	3.29	66	566	4.4	547	697	26.59	676	724	23.4	728.31	1300	22.6
	3.28	67	566	4.44	544	711	27.87	716	723	27.86	727.88	1305	25.1
	3.29	74	562	4.42	556	702	24.67	714	716	24.65	729.08	1294	20.54
	3.28	61	574	4.63	552	710	26.93	724	722	26.92	736.42	1156	22.12
C	**3.28**	**66.92**	**566.8**	**4.46**	**548.17**	**701.0**	**26.028**	**703.0**	**719.0**	**24.99**	**731.1**	**1272.2**	**23.23**
	3.28	23	623	4.63	538	711	26.76	679	738	24.56	726.47	1362	19.83
	3.31	63	582	4.49	542	664	27.18	680	688	25.81	723.77	1317	23.15
	3.28	72	582	4.63	554	764	21.53	714	778	21.51	727.46	714	25.88
	3.28	32	572	4.67	517	719	24.99	720	732	24.97	735.05	1321	22.82
	3.29	73	558	5.11	567	705	26.03	684	714	25.88	708.45	1272	23.7
D	**3.29**	**52.79**	**583.4**	**4.7**	**543.61**	**712.6**	**25.298**	**695.6**	**730.0**	**24.55**	**724.2**	**1197.2**	**23.08**

RELATIVE EXPANSION OF POWDER MIXTURES   Table 5

[%]	Maximum expansion [%]	Collapse [%]	Porosity [%]
	73.84	-5.53	83.20
	78.14	-9.54	85.50
	78.22	-8.59	85.06
	77.43	-7.75	86.58
	79.94	-14.46	86.00
A	**77.51**	**-9.17**	**85.35**
	82.51	-11.28	86.85
	75.52	-8.22	83.58
	79.00	-10.50	85.78
	76.34	-13.97	84.55
	77.13	-7.66	85.06
B	**78.10**	**-10.32**	**85.25**
	84.04	-7.56	88.70
	81.86	-7.38	87.30
	83.41	-6.58	88.43
	79.90	-7.00	86.21
	82.40	-18.90	87.08
C	**82.32**	**-9.48**	**87.61**
	78.49	-8.47	85.80
	81.92	-7.19	87.49
	82.22	-0.56	88.74
	82.43	-16.57	87.44
	81.18	-14.54	87.81
D	**81.25**	**-9.46**	**87.53**

$$Maximum = \frac{E_{max} - E_{start}}{E_{max}} * 100 \qquad (1)$$

$$Collapse = \frac{E_{end} - E_{max}}{E_{max}} * 100 \qquad (2)$$

$$Porosity = \frac{E_{end}}{E_{end} + E_{null}} * 100 \qquad (3)$$

Maximum- maximum of foam expansion
Collapse- foam collapse
Porosity- porosity measured by expandometer
E_{null}- height of sample at the start of experiment
E_{start}- value of expansion at the begining of foaming
E_{max}- maximum foam expansion
E_{end}- foam height at the end of experiment

SUMMARY

From comparison of obtained results it can be concluded that the main influence on foaming of powder mixtures has the size of used aluminium powder. Modification of blowing agent (TiH$_2$) by heat treatment has no significant and considerable influence.
The mixtures, which contain coarser aluminium powder, achieve higher values of expansion and they have the higher final porosity. Collapse of foams prepared of particular mixtures is not so different. As can be seen, the mixtures with coarser aluminium powder and with different sort of TiH$_2$ have practically same porosity. Whereas for mixtures containing finer aluminium powder it is possible to suppose that influence on the porosity has also the treatment of TiH$_2$. From mentioned results it can be concluded that by using as received fine TiH$_2$ we achieve stable foam structure (i.e. lower rate of collapse).
According to cross- sections of random chosen samples it could be said that foam made with finer aluminium powder has more homogenous structure and pores are smaller. On the other hand foam made of powder mixture containing coarser aluminium powder has higher expansion and lower collapse.
To accurately investigate the influence of shape and size of aluminium powder on foaming it seems essential to do other experiments with thicker fraction of aluminium powder between 400 - 200µm. Also it will be necessary to perform more experiment for particular mixture under the same conditions.
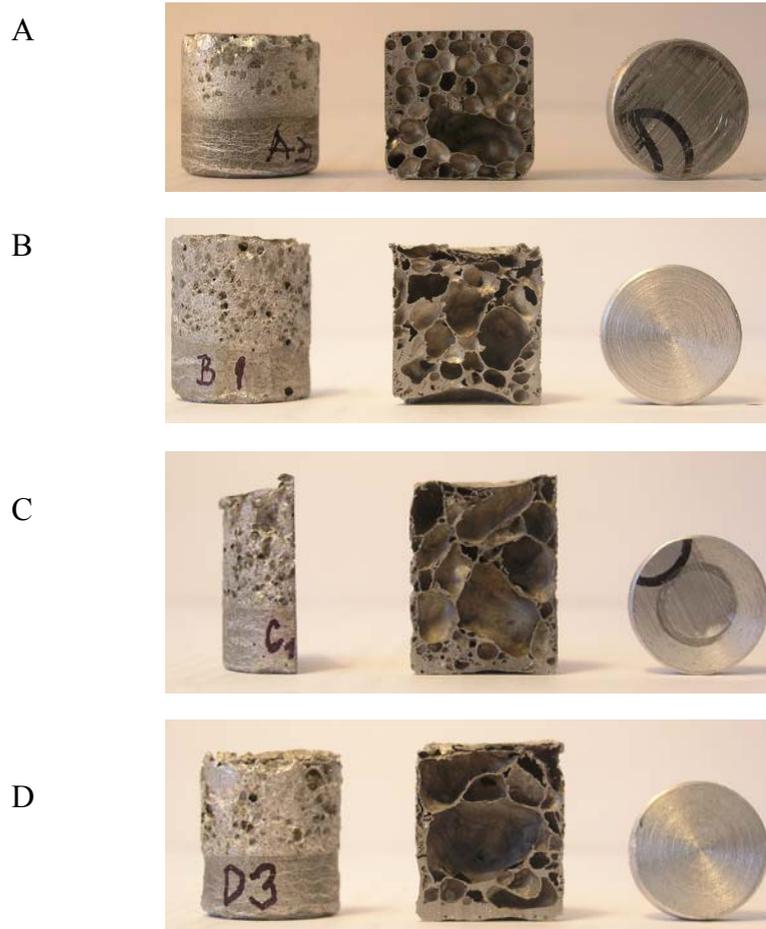
Fig. 2. *Cross- section of precursors tablets after foaming*
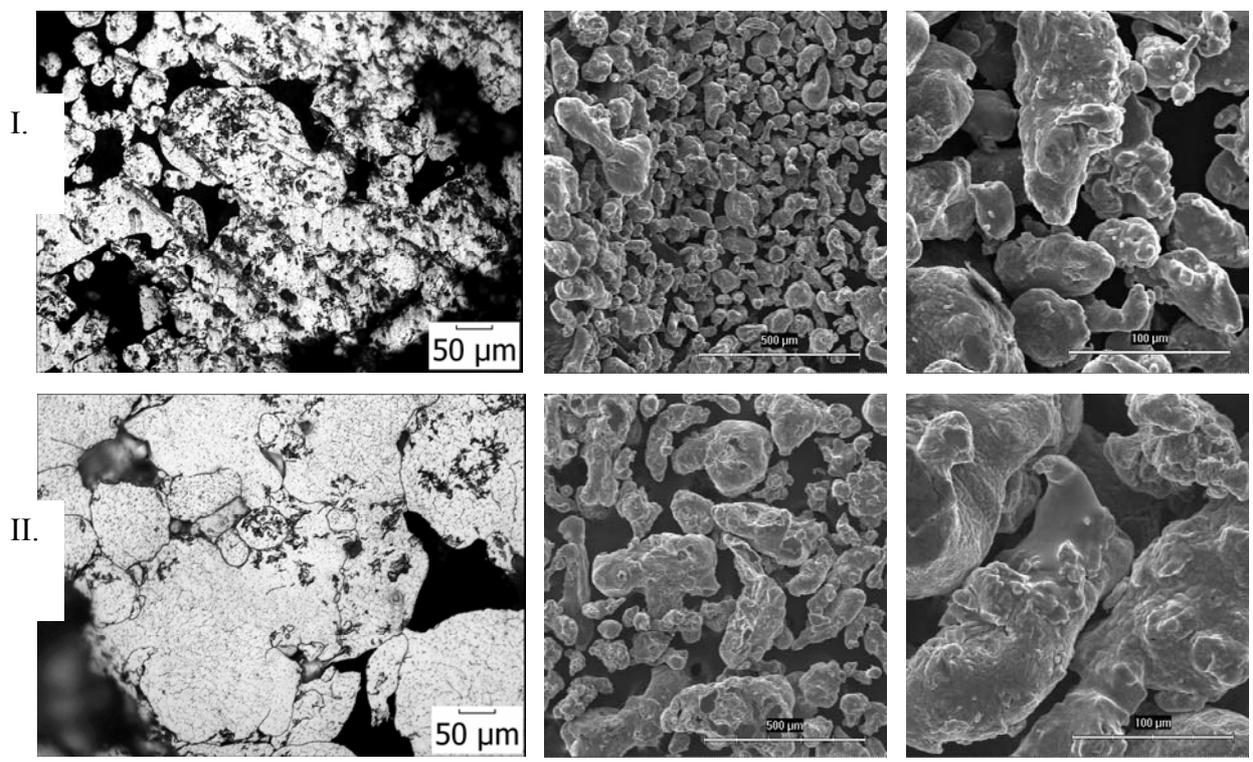
Fig. 3. *Microstucture of aluminium powder (I. size <200μm; II. size <400 μm), light microscopy and scanning electrone microscopy*

Acknowledgment

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