The Characteristics of the Granular State of Ceramic Particles in the Aspect of Producing Metal-Ceramic Composite Layers in Molds

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Abstract

The paper presents selected granular ceramic materials available on the Polish market. Their characteristics have been determined in the aspect on application in the production of iron alloy-ceramic composite. The possibility of obtaining a composite layer by means of bulk grains in molds of plates were considered, which was the foundation for experimental molds to be used in service tests. On the basis of obtaining results was stated that the knowledge of the characteristics of bulk grains enables the calculation of their quantity necessary for the composite production. When using the bulk grains the thickness of the composite layer is restricted by the thermal relations (cooler) and the physical phenomena (buoyancy, metal static pressure). Increasing amount of grains above definite condition causes surface defects in the castings. Each casting, due to its weight, shape and place of composite layer production requires an individual approach, both at the stage of formation and that of calculation of the required quantity of ceramic grains.

Keywords: Ceramics, Composite, Cast iron, Granular, Properties

1. Introduction

The increasing requirements set to working elements cast operated under intense abrasion conditions induced the direction of tests and their applications towards the issues related to production of abrasion resistant composites, iron-ceramic alloys [1,2,3].

No complete composites are to be produced in the molds; their production will be limited to a certain composite layer in the most critical points of the mold, which usually increases the abrasion resistance [4-9].

The layers are 15 to 50 mm thick, reaching 70 mm [4,10,11], even in the case of large molds as this is the usual wearing thickness of elements replaceable under normal operating conditions, e.g. 40 mm-thick sinter chute lining plates are replaced upon 50% wear,

crusher stroke strips are turned or replaced when the protruding elements of the rotator are worn down to the depth 35-70 mm, depending on the crusher's size. In the abrasion resistant composites, such as: cast iron-ceramic alloys, mineral grains play a very important role, mainly through their type and size. As far as type is concerned, the varieties of electrocorundum and carborundum are worth attention, both due to their availability in Poland and relatively low price. Their high hardness, around 9 Mohs, makes them applicable in the production of various types of grinding wheels and abrasive products as well as the abrasive for blast cleaning of steel elements. Abrasive products and the grains, however, are usually very brittle [1,4,5]. Therefore, the combination of ceramics and metal (cast iron or cast steel) is offered in the form of a composite result in excellent abrasion resistance with sufficient resistance properties, including even

impact resistance. The composite layers known so far in iron alloys are produced with the use of a ceramic profile, which is put in the appropriate location within the mold and poured over with molten metal. Mainly, in the case of plates, with large working surface (S) as compared to their thickness (h) e.g.: S/h > 100 of which h = 30-40 mm minimum, the use of ceramic inserts (profiles) creates some issues, related to mounting and the very infiltration with molten metal. Accordingly, the application of bulk ceramic grains in a metal mesh capsule may become an easier solution. For the production of the proper composite layer, we must not only select appropriate grains, but we also need to become familiar with the characteristics of the granular state and apply corresponding casting technology [5,6,10].

2. Types of ceramic grains

As it has already been mentioned in the introduction to this paper, it is mainly the electrocorundum (Al_2O_3) and carborundum (SiC) that deserve attention in the production of composite layers. Other oxides, e.g.: ZrO_2 , TiO_2, etc. are also useful, but they are practically ignored, because of price and appropriate granulation unavailable in Poland, unless they appear as impurities of electrocorundum itself.

The preferred grain sizes in iron alloys range from 1 to3 mm [12] (according to FEPA it corresponds to the F20 –F8 designation), while the preferred shape should be approximate to spherical (it assures the lowest tension values during solidification of the composite layer of the mold). In reality the said materials contain polyhedral grains [13], they are sharp-edged (Fig. 1) with variable size grains within one designation.

Designation and dimensions (in **μm)** of selected electrocorundum grains[14,15]:

F8   2360 – 2800
F10   2000 – 2360
F12   1700 – 2000
F14   1400 – 1700
F16   1180 – 1400
F20   1000 – 1280.

Several electrocorundum types can be distinguished [14,15,16]:
–   precious electrocorundum (white) containing 99% Al_2O_3,
–   semi-precious electrocorundum (grey) containing 97% Al_2O_3,
–   normal electrocorundum (brown) containing 95% Al_2O_3 and 3% TiO_2,
–   chromium (pink) electrocorundum containing 95% Al_2O_3 and up to.1% Cr_2O_3,
–   zirconium electrocorundum containing 75-80% Al_2O_3 and 20-25% ZrO_2.

All types of electrocorundum are synthetic materials produced as a result of melting of pure aluminum oxide in an arc furnace (white e-corundum) or bauxite (brown e-corundum) with possible additions of titanium, chromium, zirconium oxides. Their hardness is around 9 Mohs, specific density around 3,9-4 g/cm^3 and they may contain impurities in the form of Fe_2O, SiO_2, MgO, CaO, Na_2O, K_2O.

The precious electrocorundum is the most brittle type, while the zirconium electrocorundum has the best ductility and mechanical

strength [14, 16]. Unfortunately the latter, especially the one with preferable granularity for composites is unavailable on the Polish market. Therefore, the white and brown electrocorundum was selected for the tests, mainly due to the contrast with metal during the possible visualization of distribution and location of grains in the composite.

In addition to electrocorundum, carborundum, SiC, also deserves attention. It can occur in two varieties [15,16]:
–   green carbocorundum containing 99% SiC – very hard, but also relatively brittle, hardness ca. 9,2-9,5 Mohs, density 3,15-3,2 g/cm^3,
–   black carborundum containing 95-98 SiC with Fe_2O_3, Al_2O_3, SiO_2 admixtures. Its hardness and density are similar to those of green carborundum, it is less brittle, therefore selected as a possible 10-25% admixture to electrocorundum.
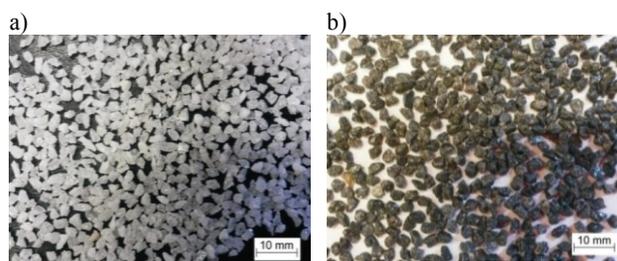
Fig. 1. Ceramic grains: a) white electrocorundum of F12 granularity, b) brown electrocorundum of F10 granularity

In spite of the high hardness, the limitation of carborundum use is the result of its higher brittleness as compared to electrocorundum, particularly when used for composite molds being operated under dynamic heavy duty conditions (all types of plates, strips and hammers in crushing machines).

In addition to the type of grains, it is recommended to become familiar with and designate the characteristics of the granular state, which may significantly affect the composite production. They include: bulk density, bulk porosity, pore size and angle of natural stability as well as internal friction coefficient and shear stress. The parameters are designated upon annealing the grains in 120ºC. As a reference the parameters of glass spheres of 1,5-2,0 mm granularity and washed foundry silica sand of 0,16-0,35 mm granularity were provided as well as those of granulate (conglomerate) of mixture of grains with dimensions 5-11 and 12-18 mm.

3. The granular state characteristics

Specific density [15, 17] expressed by the formula:

$$q = \frac{M}{V} [g/cm^3] \qquad (1)$$

of which:
M – sample weight, [g]
V– sample volume, [cm^3].

Bulk density [17,18,19,20] calculated according to the formula:

$$q_n = \frac{M_n}{V_n} [g/cm^3] \tag{2}$$

of which:

M_n– stability volume weight, [g]

V_n – bulk volume of sample, [cm^3].

Bulk porosity [14,18] means the volumetric share of intergrain space (gaps) of bulk material and is calculated under the formula:

$$p = \frac{(q-q_n)}{q} \tag{3}$$

or in percentage

$$p = \frac{q-q_n}{q} \cdot 100\% \tag{4}$$

4. Pore size

Due to the fact that the grains accepted for tests are polyhedral and sharp-edged and of various sizes, and upon being poured into a container they touch one another in a way which is difficult to be recorded simply, i.e. it is difficult to assess the pore size. Therefore, the methodology of identical diameter balls was used in order to simplify the tests [21,22, 23, 24]. The balls (grains) of identical diameters, when poured info a container, usually assume a position approximate to utmost compaction and such compaction is characteristic for the following structures: cubic flat centered and hexagonal. Their compaction density is identical:

$$\rho_u = \pi \frac{\sqrt{2}}{6} = 0,7405 \text{ [23]} \tag{5}$$

Two types of gaps are created in them: tetraedric and octaedric (fig. 2) [21,22]:

– the tetraedric gap appears between four spheres and its dimension is $d_{gap} = 0,225 \ D_{sphere}$,

– the octaedric gap appears between six spheres and its dimension is $d_{gap} = 0,414 \ D_{sphere}$.
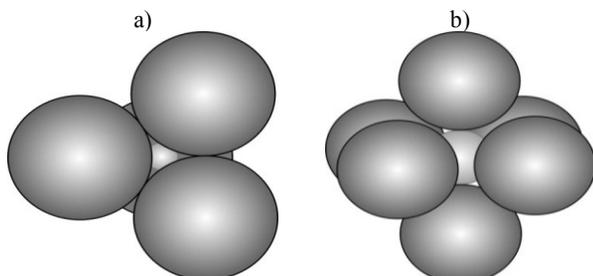
Fig. 2. Types of gaps (pores): a) tetraedric, b) octaedric [22]

According to [23, 24] in the set of densely compacted spheres there are twice as many tetraedric than octaedric, therefore, the average diameter of a pore (gap) in the set of identical spheres can be calculated out of the dependency:

$$\bar{d} = \sqrt[3]{\frac{2 \cdot d_{tet}^3 + d_{oct}^3}{3}} \tag{6}$$

of which

$$\bar{d} = 0,315 \ D_{sphere} \quad [22] \tag{7}$$

This dependency was used for approximate calculation of the size of pores of the materials discussed, where in our case D means the average grain size in mm (Table 1).

As it appears, the pore size for both electrocorundums and glass spheres in bulk state is only slightly bigger than the limit of division into capillary and non-capillary pores (d = 0,5 mm) [25] and therefore no deep penetration of molten metal into the layer of grains filling the mold cavity can be expected in the gravitational pouring process. In the case of granulates we may expect a good penetration of molten metal between the particular agglomerates, because the pore size approximately corresponds to that of the pores of the foam filters used in iron alloy foundry sector, e.g. the filter designated 10 ppi has 5 mm pore size, while the 20 ppi filter has pore size ca. 3,8 mm [26].

5. Natural stability angle

The natural stability angle for granular and dry materials approximately corresponds to the internal friction angle[18, 19]. This is the angle between the slant height of bulk grains and the base (Fig. 3).
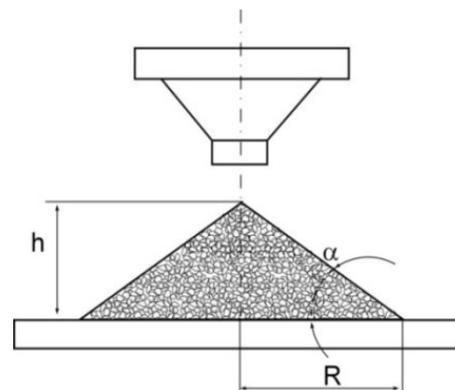
Fig. 3. Natural stability angle [19]

$$tg\alpha = \frac{h}{R} \tag{8}$$

Its value depends on the extent of mutual mobility and jamming of the grains and expresses the friction resistance values during mutual relocation of the grains. This is the angle at which the forces causing dispersion of grains balance the friction forces.

Table 1 shows the properties of selected materials from experimental measurements or calculations.

Table 1.
Properties of selected materials

Material	Specific density $\frac{M}{V}$ q [g/cm³]	Bulk density $\frac{M_n}{V_n}$ q_n [g/cm³]	Bulk porosity $\frac{q - q_n}{q} \cdot 100\%$ p [%]	Average grain size D [mm]	Average diameter of a pore (gap) $d_{śr}$ [mm]	Natural stability angle α
electrocorundum (white and brown) electrocorundums the average bulk porosity is	3,90 – 4,00		0,5 (50%)			
precious electrocorundum with F12 grain size		60/30 = 2,0		1,85	0,58	α = 37º
normal electrocorundum with F10 grain size		62/30 = 2,06		1,95	0,61	35º
carborundum	3,15 – 3,20		0,32 (32%)	1,30	0,40	32º
black carborundum with F16 grain size		65 /30 = 2,15				
glass spheres	2,40 – 2,60	45/30 = 1,5	0,4 (40%)	1,75	0,55	10º
silica sand	2,68 – 2,72	49/30 = 1,6	0,4 (40%)	0,25	0,08	23º
granulate 1		36/30 = 1,2	0,7 (70%)	8,0	2,52	30º
granulate 2		30/30 = 1,0	0,75 (75%)	15,0	4,72	28º

6. Shear strength

The shear strength is the resistance of granular material against contact stresses, e.g. during attempt to loosen the grains consisting in moving on layer of grains after another. The sear stability is determined on a test-site by means of a measuring system (Fig.4).
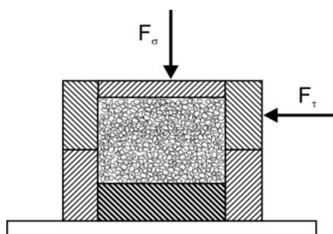
Fig. 4. Plan of test-bed for determination of shear stability in the granular layer [19]

$F\tau$ – shear stability, i.e. the minimum force acting along a specific surface,
$F\sigma$– normal force, i.e. rectangular to the shear plane,
μ – internal friction coefficient, (for bulk and dry materials this coefficient approximately corresponds to tangent of natural stabilization angle **$\mu \sim$ tg α**),
therefore the shear stability necessary for relocation of the grain layer is determined knowing the stabilization angle from the dependency:

$$F_\tau = F_\sigma \cdot tg\,\alpha \qquad (9)$$

The basic characteristics of the granular state presented herein constitute a certain aid for production of a mould with a composite layer made with the use of loose grains.

At first, however, we should present a hypothetical description of such process and then verify it under industrial conditions. An example may be a plate of dimensions 440x180x40 mm, with anticipated composite 20 mm thick layer in which the grain content was defined on the level of: A) ¼ or 25% and B) 1/3 or 33,3% , wherein their mass regarded as the chill should not exceed 5-7%, and in massive castings 6-10% mass of cooled down part of the casting [27]. It can be presented as followed:
$w = 100 \cdot M_{A(B)}/ M$ %.
Calculations of the thickness of the bulk layer of particles:
molten metal density $\qquad q_1 = 7,0$ g/cm²,
stabilization density of grains $\qquad q_2 = 2,0$ g/cm²,
plate surface $\qquad$ S = 44 x 18 = 792 cm²,
metal of heat center mass $\qquad$ M = V · q_1 = 1584 · 7 = 11 088g,
volume of the layer $\qquad$ V = S · h = 792 · 2 = 1584 cm³,
  A) Volume of grains V_A = V · 25/100 = 396 cm³,
    Mass of the grains M_A = V_A · q_2 = 792 g,
    $w = 100 \cdot M_A/M$ = approx. 7,14%,
    bulk thickness of the grains h_A = V_A / S = 0,5 cm,
  B) Volume of grains V_B = V · 30/100 = 475 cm³,
    Mass of the grains M_B = V_B · q_2 = 950 g,
    $w = 100 \cdot M_B /M$ = 8,56%,
    bulk thickness of the grains h_B = V_B / S = 0,6 cm.

7. Infiltration of grain layer with liquid metal

This layer should be put in a container made from metal mesh in the mold on the depth of ca. 25 - 30 mm and gravitationally poured over with molten metal, with supply from the bottom (Fig.5).
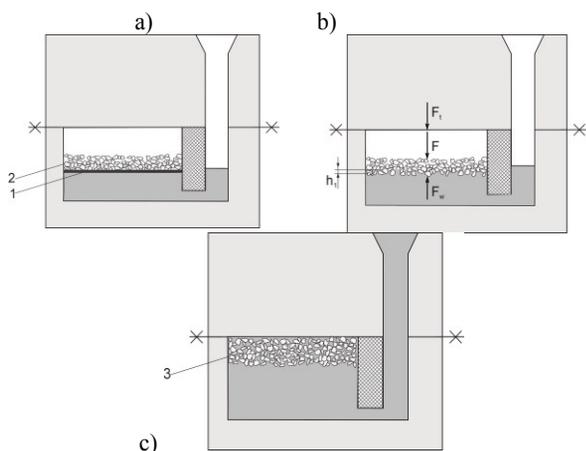
Fig. 5. The possible phases of composite layer production within a
hypothetical plate: a) phase I - on the metal mesh (1) the grains
lay still (2), their porosity p = 50% and thickness h = (5; 6) mm,
pouring over starts and lasts until the molten metal touches the
metal mesh; b) phase II - a temporary resistance of metal flow
occurs related to melting of the mesh and penetration into the
grain layer to the depth h_1; at this moment the buoyancy (F_w)
balances the gravity of the grains (F) and transverse force (F_t);
c) phase III - elevation of the molten metal in the mold with the
layer of grains being created along until it meets the upper limit of
the mold, after which, as a result of growing pressure resulting
from the height of the upper box the penetration of metal between
the grains should occur, thus creating a composite layer

Due to more than double difference in densities of both materials,
the buoyancy phenomenon should be considered. When the molten
metal (after melting of the mesh) meets the layer of grains it starts
to infiltrate it into certain height (h_1) and and jostle grains
simultaneously. Relations were enclosed in equilibrium system,
where: F_w - buoyant force; F - gravity force; F_t - transverse force
and acceleration of gravity g = 9,81 m/s^2; α = 35°, tgα = 0,7; MA1
i MB1 - bulk mass for 25 i 33,3 % volume of respectively.
$$F_w = F + F_t \quad ; \quad F_t = F \, tg\alpha$$

$$S \cdot h_{A1} \cdot q_1 \cdot g = M_{A1} \cdot g \, (1 + tg\alpha)$$
$$S \cdot h_{B1} \cdot q_1 \cdot g = M_{B1} \cdot g \, (1 + tg\alpha)$$

Therefore, the depth of submerging of the layer of grains in the
molten metal is respectively:
$$h_{A1} = 1,7 \cdot M_{A1} /S \cdot q_1 = 1,7 \cdot 792 / 792 \cdot 7 = 0,24 \, cm = 2,4 \, mm,$$
$$h_{B1} = 1,7 \cdot M_{B1} /S \cdot q_1 = 1,7 \cdot 950 / 792 \cdot 7 = 0,29 \, cm = 2,9 \, mm.$$

Thus, when the molten metal presses from the bottom (upon
melting the metal mesh) the penetration of the layer of grains to the
depth of ca. 1,4 mm should take place. At the same time, along with
elevation of table of metal the entire layer is elevated (the layer of
grains floats partly submerged in the molten metal) until the
moment of resistance against the upper wall of the mold. Then, as
a result of metal static pressure of ca. 14 kPa (resulting from the
height of the upper box -200 mm) the further penetration of molten
metal between the grains should occur as well as the required
composite layer should be produced [1].

The above considerations have been subjected to verification by
appropriate experiment under industrial conditions. For this
purpose appropriate model was made including the formation of
the plane in the bottom box in the molding compound with
bentonite.

The properly prepared metal mesh was put on and reasonably
evenly dosed amount of electrocorundum grains F10(0,79 kg to the
first, and 0,95 to the second) was poured over (Fig.6).
Next the molds was closed and poured over with molten chromium
cast iron of 1610°C temperature measured in the tub. After cooling,
the casting was forged out of the mold, cleaned and subjected to
external visual inspection. Casting containing 0,95 kg of grains was
aborted, because free electrocorundum grains caused wide surface
defect, what disqualifies the casting (Fig.7). The casting contatning
0,79 kg of grains was correct, devoid of defects (Fig.8a). The cross-
section of the plate is presented in Fig. 8b. The thickness of
composite layer is 8-12 mm. 6 plates were produced in this way.
They were subjected to heat treatment, painted, aimed at
identification and they were given to utilisation.
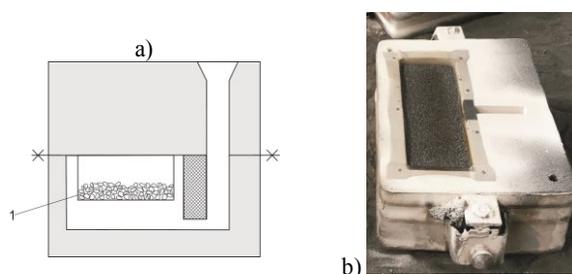
Fig. 6. Crossection of mould(a) with a layer of stabilized grains
(1) on metal mesh; (b) mould drag

Fig. 7. Casting containing 0,95 kg of electrocorundum grains
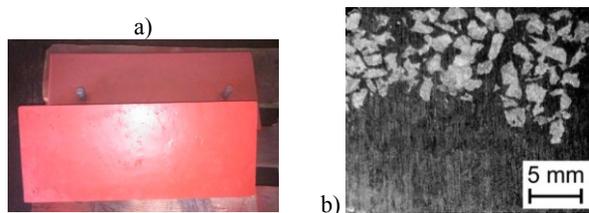
Fig.8. Castings containings 0,79 kg of electrocorundum grains,
two holding-down bolt (a);
Composite layer of the thickness of 8 – 12 mm (b)

On the surface, grains area which are not fixed with the metal.

Researches
Chromium cast iron plates with composite layer and plates made of
Nihard 4 cast iron were mounted on sliding hole of sinter and
subjected to utilisation. After approx. 6 months they were

dismounted, cleaned and subjected to visual observation. There is no distinctive differences between plates, they were used at similar level. Further research will include considerations influence of coefficient of thermal expansion. Significant difference in the thermal expansion coefficient between ceramics and metal matrix, may negative affect to the internal stresses distribution in the composite material [28].

8. Conclusions

1. The knowledge of the characteristics of bulk grains enables the calculation of their quantity necessary for the composite production,
2. When using the bulk grains the thickness of the composite layer in a plate is 8-12 mm (achieving assumed thickness- 20 mm is unlikely using gravity casting,
3. Increasing amount of grains above w>8 causes surface defects in the castings.
4. The results of researches did not confirm favorable influence of composite layer presence on usable properties of material (the thickness of composite layer was not sufficient)
5. Each casting requires individual approach as to the mass, the shape and zone where composite layer will be produced, at the stage of founding technology, as amount and character of ceramic grains (free or fixed).

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