ARCHIVES
of
FOUNDRY ENGINEERING
DOI: 10.1515/afe-2016-0027
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences
ISSN (2299-2944)
Volume 16
Issue 2/2016
61 – 68

Determination of Unit Pressure Force in Material Volume in the Course of Refractory Stamping Press Moulding

A.W. Orłowicz [a]*, M. Mróz [a], Z. Cisek [a], M. Tupaj [a], A. Trytek [a], B. Kupiec [a], M. Korzeniowski [a], K. Sondej [b], L. Kozak [b]
[a] Rzeszow University of Technology, Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
[b] ZM Service Sp. z o.o., ul. Przemysłowa 1, 39-100 Ropczyce, Poland
*Corresponding author. E-mail address: aworlow@prz.edu.pl

Received 31.03.2016; accepted in revised form 22.04.2016

Abstract

The paper presents results of assessment of the unit pressure force within the refractory material volume in the course press-moulding of stampings for refractory precast shapes. The force was evaluated with the use of physical simulation of deformation undergone by lead balls placed in the raw refractory mass subjected to pressing in a metal die. To determine the value of unit pressure force applied to the aggregate grains in the course of stamping press-moulding, physical model of deformation of a sphere induced by the uniaxial stress state was used.

Keywords: Die stamping, Refractory materials, Metal die, Material density

1. Introduction

Production of precast shapes from refractory materials for casting ladles and metal smelting furnaces includes the process of press moulding, drying, and firing of stampings. The press moulding is an important stage of the process decisive for susceptibility of stampings to cracking in the course of drying and firing. It influences also the service properties of fired refractory shapes which depend on density of the material and thus also on its porosity. The latter in turn affects thermo-physical properties of the final product. On the other hand, excessive porosity of refractories facilitates penetration of liquid slugs and gases which accelerate degradation of stampings.

Density of material in a stamping is affected by the impenetrable metal die and the press moulding technique. Fig. 1 shows a schematic diagram and a 3D view of a three-cavity die used to produce stampings.

From the bottom, die cavity orifices are reproduced by means of a three-segment floating punch, and from the top, with a three-segment pressing plunger. Die cavities are filled with magnesite-chromite aggregate with a binder which typically is the sulphite liquor.

To reduce porosity of stampings, the press moulding process was a staged cycle comprising four pressing phases and four deaeration phases, the latter consisting in releasing the plunger load. The successive phases were carried out with increasing values of the pressing plunger load. A registered course of the stamping compaction cycle is presented in Fig. 2. The last stage of production of stampings is pushing them out from the die cavity.

In the course of compacting material in die cavities, a complex stress state arises in a stamping. On the other hand, the mass is pressed against the die walls resulting in wearing their surfaces.

Die walls are reconstructed by replacing consumable steel inserts. To reduce the cost of making stampings, Zakłady Magnezytowe Ropczyce S.A. [*Ropczyce Magnesite Works plc.*] and their competitors carry out studies on improvement of structural design of and variant materials for die inserts.

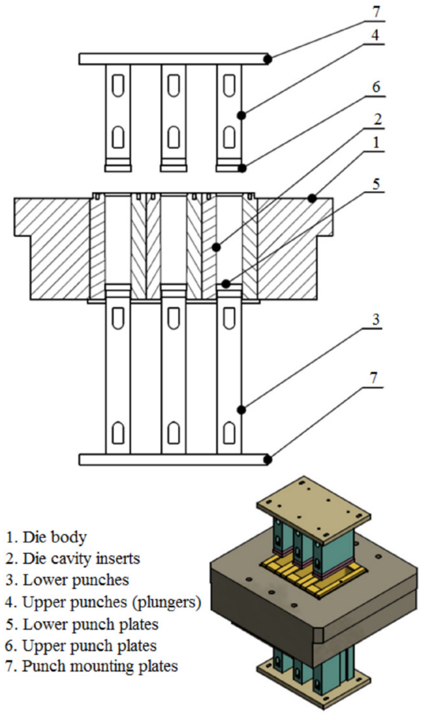


Fig. 1. A schematic diagram and a 3D view of the three-cavity die for producing stampings

In the course of compacting material in die cavities, a complex stress state arises in a stamping. On the other hand, the mass is pressed against the die walls resulting in wearing their surfaces.

Die walls are reconstructed by replacing consumable steel inserts. To reduce the cost of making stampings, Zakłady Magnezytowe Ropczyce S.A. [*Ropczyce Magnesite Works plc.*] and their competitors carry out studies on improvement of structural design of and variant materials for die inserts.

To test new insert designs, higher values of press moulding forces are usually adopted.

From both scientific and practical point of view it is important to gain a new knowledge on stress states and values existing in the stamping material, especially in the areas reproduced by die inserts, as this provides information about load exerted on inserts by the mass.

Service life of die inserts depends on properties of the material and value of load applied to the mass moving over working insert surfaces. It is necessary to bear in mind that aggregate particles have sharp edges and are characterised with high hardness. For instance, dimensions of magnesite-chromite aggregate particles range from 2.7 mm to 3.9 mm, and their edge angles range from 50° to 110°. Hardness of the particles in the ten-degree Mohs scale is 7, with hardness of diamond being attributed hardness equalling 10.

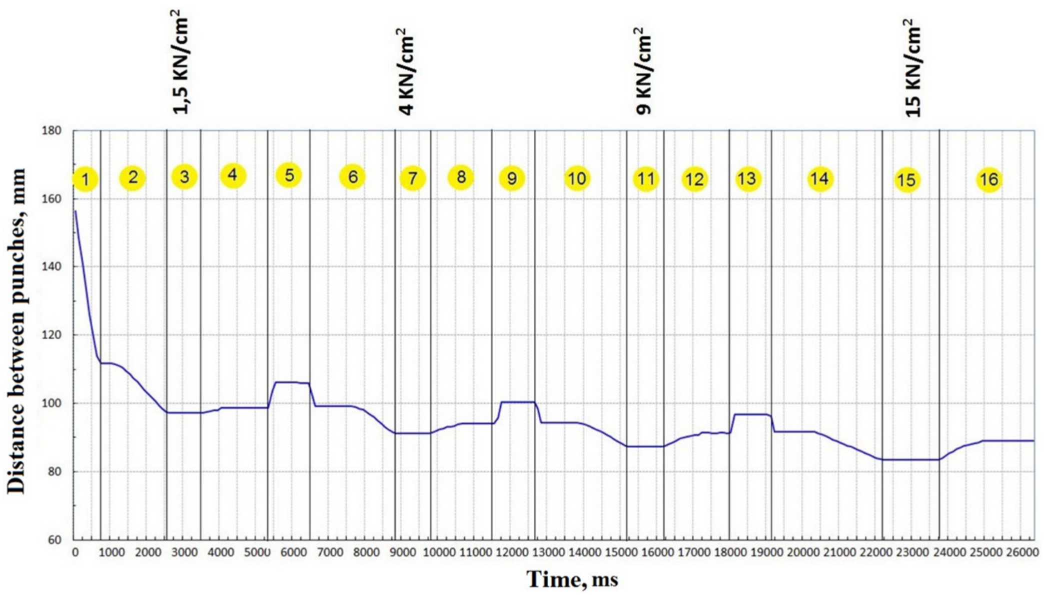


Fig. 2. The course of raw mass compaction in the three-cavity metal die on LAEIS HPF 1250 press: 1 - plunger lowering under its own weight; 2 - pressing up to a preset deaeration pressure (phase 1); 3 - holding the deaeration pressure for a preset time (phase 1); 4 - releasing the deaeration pressure (phase 1);5 - retracting the plunger up by a preset distance; 6 - pressing up to a preset deaeration pressure (phase 2); 7 - holding the deaeration pressure for a preset time (phase 2); 8 - releasing the deaeration pressure (phase 2); 9 - retracting the plunger up by a preset distance; 10 - pressing up to a preset deaeration pressure (phase 3); 11 - holding the deaeration pressure for a preset time (phase 3); 12 - releasing the deaeration pressure (phase 3);13 - retracting the plunger up by a preset distance; 14 - final pressing up to a preset final pressure; 15 - holding the final pressure; 16 - releasing the final pressure

The objective of the study reported in this paper was to evaluate the unit pressure which occurs in the process of press-moulding of stampings, in particular in the areas adjacent to die insert surfaces.

2. Description of experiment and methodology

The base for calculations of the unit pressure force value within the material volume in the course of stamping press-moulding were the results of physical simulation of deformation sustained by lead balls inserted into the raw refractory material mass in the course of production of stampings.

The balls were placed in the material with the LAEIS HPF 1250 press operating in manual mode, as in the automated cycle, the whole volume of cavities is filled at once. The normal charge of mass filling a die cavity was divided into 6 portions. After placing and levelling the first portion of mass in a cavity, operator stuffed individual balls into its surface. After pouring in and levelling another portion of the mass, the operation of stuffing successive set of balls into the mass was repeated (Fig. 3).

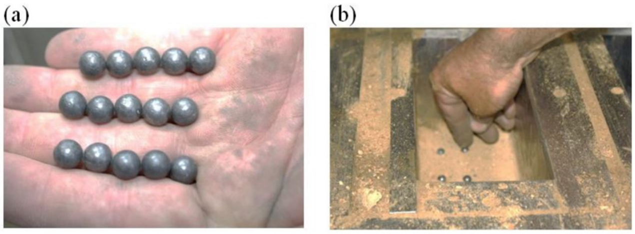


Fig. 3. (a) A view of lead balls prepared for placing in a single layer; (b) the scheme of placing balls on mass surface

Lead balls were press-moulded in 6 layers along the stamping height. In each layer, 5 balls were included in each of three rows (a total of 15 pieces for each layer).

An example view of individual layers with balls stuffed into them is shown in Fig. 4.

The next stage of the experiment consisted in pressing the mix.

Position of balls in the stamping was identified with the number of ball in a layer and the layer number (Fig. 5).

Correctness of spatial distribution of lead balls was tested and their deformation provisionally assessed by means of radiographic method. The examination was carried out with the use YXLON Y.MU2000 X-ray inspection system. Fig. 6 shows an example radiograph of the stamping with lead balls distributed within its volume.

Analysis of the performed radiographs indicated that as a result of the press moulding process, the balls underwent flattening in the direction coincident with direction of the pressing force. This suggests that in the press moulding process, the forces with highest values were oriented in the direction of displacement of the pressing punches. The observation does not exclude presence of forces pressing the mass towards the die walls, but values of these forces were much lower and were not reflected in the shape of balls.

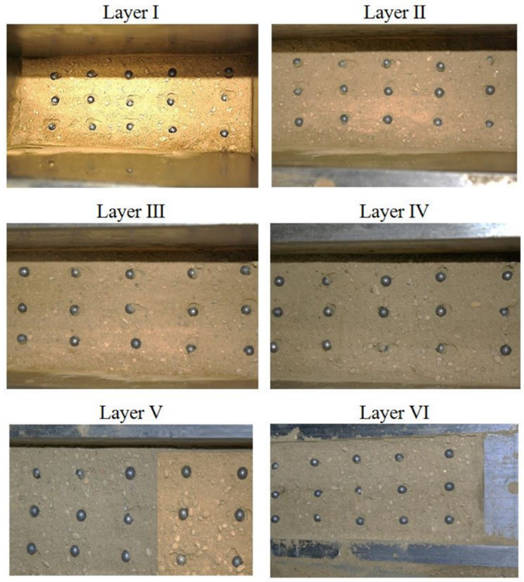


Fig. 4. A view of surfaces of Layers I–VI in successive stages of filling the die cavity with mass and balls stuffed into it

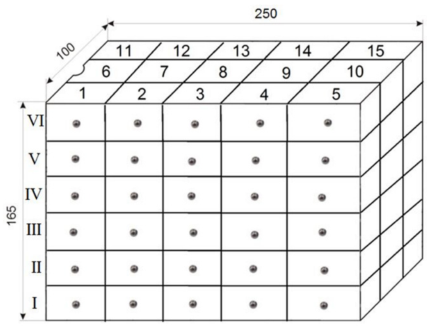


Fig. 5. The scheme used to identify position of balls in the stamping

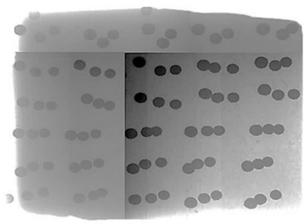


Fig. 6. Radiographic image of the stamping with well-visible deformed lead balls

To take measurements of the geometry representing plastic deformation of the balls, the stamping was soaked with water and its successive layer removed by gentle crumbling.

For the purpose of evaluation of the unit pressure force based on results of measurements of deformation of lead balls it has been assumed that:

- direction of the thrust force coincides with the direction of press moulding force (Fig. 7);
- the analysis pertains to deformation of balls under an uniaxial state of stress;
- the calculated values of pressure force applied to individual balls (unit pressure forces) distributed within the stamping volume equal the unit pressure forces exerted on mass grains adjacent to the balls.

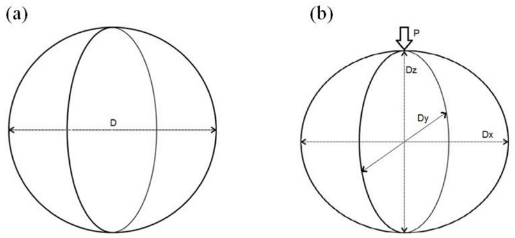


Fig. 7. Geometry of a sphere (a) before plastic deformation and (b) after uniaxial plastic deformation

Input data for calculations:
- lead ball diameter before deformation: D = 8.5 mm;
- lead ball diameters after deformation;
- lead ball hardness: 3 HB (29.43 MPa).

A drawing showing schematically the ball parameters measured after plastic deformation is presented in Fig. 8.

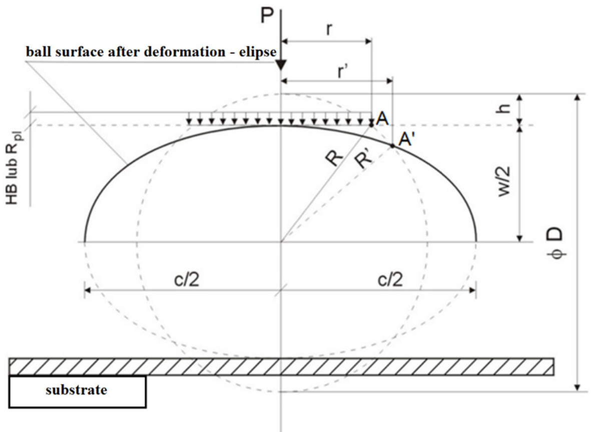


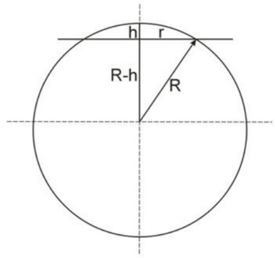
Fig. 8. A diagram showing ball deformation after exceeding the yield point: P - pressure force, D - ball diameter before deformation; R - ball radius before deformation at point A; R' - ball radius after deformation (ellipsoid) at point A′ (point A after deformation); r - adius of the ball-mass contact surface in the course of pressing before deformation at point A; r' - radius of the ball-mix contact surface (ellipsoid) after deformation in the course of pressing at point A′; w - ball diameter after deformation measured in direction of pressure force (along Z axis); h - ball deformation value defined as the difference of ball radius before deformation and ball radius after deformation measured in direction of the pressure force w; c - ball diameter after deformation measured in direction perpendicular to the pressure force (c' - along X axis, c'' - along Y axis); HB - ball material hardness; R_{pl} - ball material yield strength

Value of the pressure force exerted on the ball after exceeding the yield point can be determined from the formula:

$$P = \pi r^2 R_{pl} \approx \pi r^2 HB \tag{1}$$

where P is the value of force exerted on the ball, r - radius of the ball-mass contact surface in the course of pressing before deformation at point A (mm), R_{pl} - the yield strength (MPa), and HB - the Brinell hardness (MPa)

The radius of the ball-mass contact surface in the course of pressing before deformation at point A was determined according to scheme shown in Fig. 9.



$$R^2 = (R - h)^2 + r^2$$
$$r^2 = 2Rh$$
$$h = 0.5\,(D - w) \quad \text{(Fig. 8)}$$
$$r^2 = 0.5D(D - w) \tag{2}$$

Fig. 9. Illustration of the method used to calculate the radius of ball-mass surface in the course of press moulding at point A; r - radius of the ball-mass contact surface in the course of pressing before deformation at point A; R - ball radius before deformation at point A; D - ball diameter before deformation; h - ball deformation value defined as the difference of ball radius before deformation and the ball radius after deformation measured in direction of the pressure force; w - ball diameter after deformation measured along direction of the pressure force (along Z axis)

Substituting (2) to (1), one obtains expression allowing to calculate the unit pressure force:

$$P = 0.5\pi D(D - w)HB \tag{3}$$

where P is the pressure force, D - ball diameter before deformation (mm), w - ball diameter after deformation measured along direction of the pressure force (along Z axis, mm), and HB hardness value (MPa).

3. Results of measurements

Results of measurements of the geometry of plastically deformed lead balls press-formed within the stamping volume and results of calculation of the pressure force which was the cause of the deformation are presented in Table 1.

Example distributions of value of the unit pressure force exerted on test balls in individual layers of the stamping in the course of its fabrication are presented in Figs. 10–12. It has been assumed that unit pressure forces acting on lead balls equal the unit pressure forces exerted on matrix grains. For this reason, in captions of Figs. 10–12, the term “unit pressure force on matrix grains” was used.

Table 1.
Results of measurements of the geometry of deformed lead balls and results of calculation of the unit pressure force being the cause of the deformation

	Ball number	D, mm	Ball position co-ordinates			w, mm	P, N
			X, mm	Y, mm	Z, mm		
Layer II	61	8,5	17	25	123	7,77	284,5
	62	8,5	17	75	123	7,81	269,3
	63	8,5	17	125	123	7,85	256,7
	64	8,5	17	175	123	7,82	268,4
	65	8,5	17	225	123	7,77	285,0
	66	8,5	50	25	123	7,80	275,6
	67	8,5	50	75	123	7,84	258,5
	68	8,5	50	125	123	7,88	245,0
	69	8,5	50	175	123	7,84	260,0
	70	8,5	50	225	123	7,80	275,6
	71	8,5	84	25	123	7,77	287,2
	72	8,5	84	75	123	7,80	272,9
	73	8,5	84	125	123	7,83	262,1
	74	8,5	84	175	123	7,80	272,9
	75	8,5	84	225	123	7,76	290,0
Layer I	76	8,5	17	25	140	7,71	310,0
	77	8,5	17	75	140	7,74	296,6
	78	8,5	17	125	140	7,76	292,2
	79	8,5	17	175	140	7,74	296,6
	80	8,5	17	225	140	7,70	313,8
	81	8,5	50	25	140	7,73	303,4
	82	8,5	50	75	140	7,76	290,3
	83	8,5	50	125	140	7,78	282,5
	84	8,5	50	175	140	7,76	290,0
	85	8,5	50	225	140	7,71	310,0
	86	8,5	84	25	140	7,70	315,0
	87	8,5	84	75	140	7,72	305,0
	88	8,5	84	125	140	7,73	301,7
	89	8,5	84	175	140	7,72	306,0
	90	8,5	84	225	140	7,68	320,7

	Ball number	D, mm	Ball position co-ordinates			w, mm	P, N
			X, mm	Y, mm	Z, mm		
Layer IV	31	8,5	17	25	68	7,77	285,9
	32	8,5	17	75	68	7,81	271,2
	33	8,5	17	125	68	7,82	266,9
	34	8,5	17	175	68	7,79	277,3
	35	8,5	17	225	68	7,76	289,4
	36	8,5	50	25	68	7,80	273,8
	37	8,5	50	75	68	7,84	260,8
	38	8,5	50	125	68	7,85	255,0
	39	8,5	50	175	68	7,82	265,0
	40	8,5	50	225	68	7,78	281,6
	41	8,5	84	25	68	7,76	290,0
	42	8,5	84	75	68	7,80	276,4
	43	8,5	84	125	68	7,80	275,0
	44	8,5	84	175	68	7,78	283,3
	45	8,5	84	225	68	7,75	292,9
Layer III	46	8,5	17	25	95	7,89	237,6
	47	8,5	17	75	95	7,92	227,0
	48	8,5	17	125	95	7,93	223,5
	49	8,5	17	175	95	7,92	228,8
	50	8,5	17	225	95	7,88	242,0
	51	8,5	50	25	95	7,93	224,3
	52	8,5	50	75	95	7,96	211,9
	53	8,5	50	125	95	7,97	206,6
	54	8,5	50	175	95	7,95	215,0
	55	8,5	50	225	95	7,92	227,9
	56	8,5	84	25	95	7,87	246,5
	57	8,5	84	75	95	7,91	232,3
	58	8,5	84	125	95	7,91	230,5
	59	8,5	84	175	95	7,89	237,6
	60	8,5	84	225	95	7,86	250,0

	Ball number	D, mm	Ball position co-ordinates			w, mm	P, N
			X, mm	Y, mm	Z, mm		
Layer VI	1	8,5	17	25	13	7,68	321,2
	2	8,5	17	75	13	7,69	316,2
	3	8,5	17	125	13	7,71	311,7
	4	8,5	17	175	13	7,70	312,3
	5	8,5	17	225	13	7,68	320,0
	6	8,5	50	25	13	7,69	319,6
	7	8,5	50	75	13	7,71	311,7
	8	8,5	50	125	13	7,72	306,4
	9	8,5	50	175	13	7,71	308,4
	10	8,5	50	225	13	7,69	316,2
	11	8,5	84	25	13	7,67	324,5
	12	8,5	84	75	13	7,69	319,5
	13	8,5	84	125	13	7,70	315,0
	14	8,5	84	175	13	7,69	316,3
	15	8,5	84	225	13	7,68	322,2
Layer V	16	8,5	17	25	40	7,73	302,1
	17	8,5	17	75	40	7,76	291,8
	18	8,5	17	125	40	7,77	285,0
	19	8,5	17	175	40	7,76	289,0
	20	8,5	17	225	40	7,73	302,1
	21	8,5	50	25	40	7,75	295,5
	22	8,5	50	75	40	7,78	284,3
	23	8,5	50	125	40	7,79	278,6
	24	8,5	50	175	40	7,78	281,5
	25	8,5	50	225	40	7,74	297,4
	26	8,5	84	25	40	7,72	305,0
	27	8,5	84	75	40	7,74	297,4
	28	8,5	84	125	40	7,76	290,0
	29	8,5	84	175	40	7,75	295,5
	30	8,5	84	225	40	7,72	305,0

Deformations of lead balls, determined on the grounds of the change occurring in their diameters in the direction coincident with direction of pressure force, ranged from 7.67 mm to 7.97 mm (Table 1). The largest deformation of balls was observed in Layers I, II, V, and VI, and the smallest in Layer IV. This is reflected in values of the calculated pressure force which falls in the range from 206.6 N to 322.2 N.

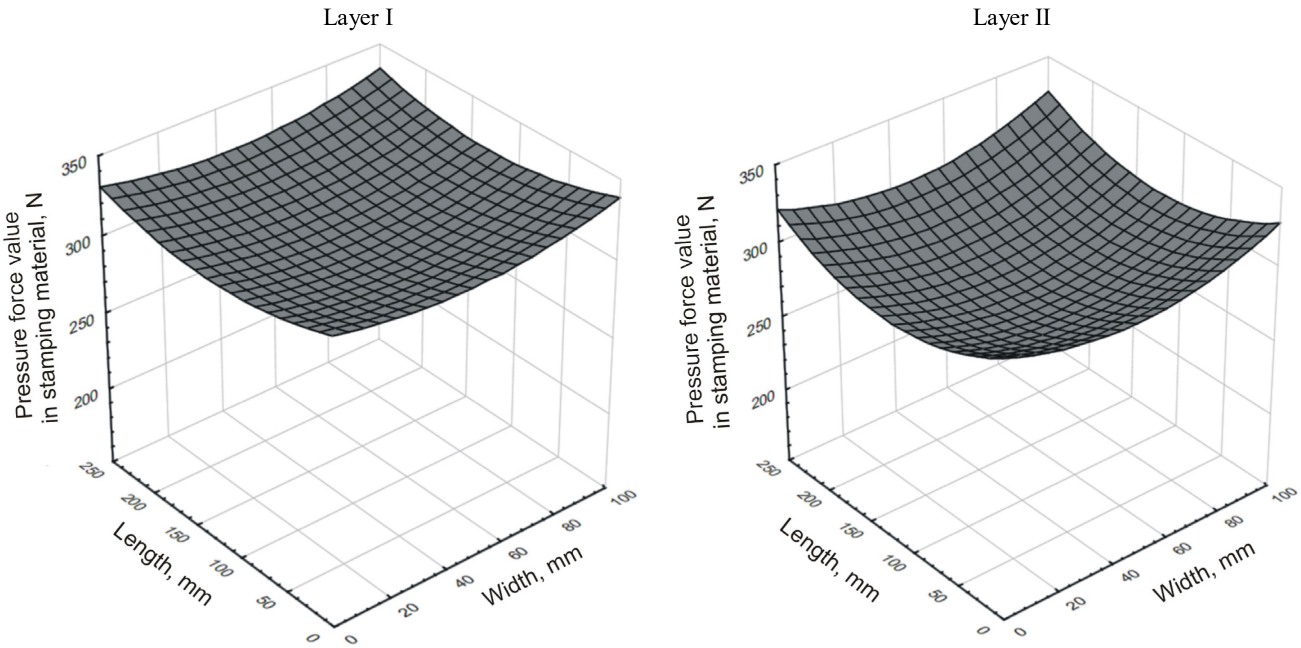


Fig. 10. Distribution of values of the unit pressure force on matrix grains in Layers I and II of the stamping

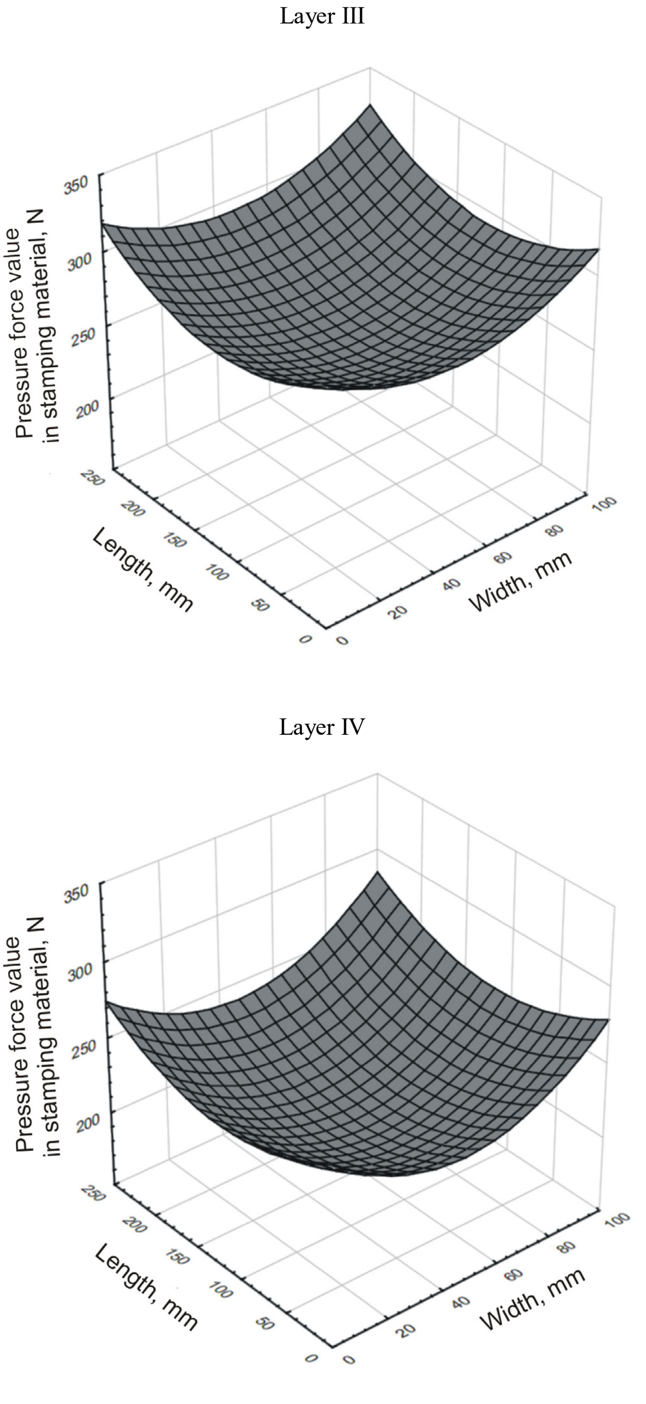


Fig. 11. Distribution of values of the unit pressure force on matrix grains in Layers III and IV of the stamping

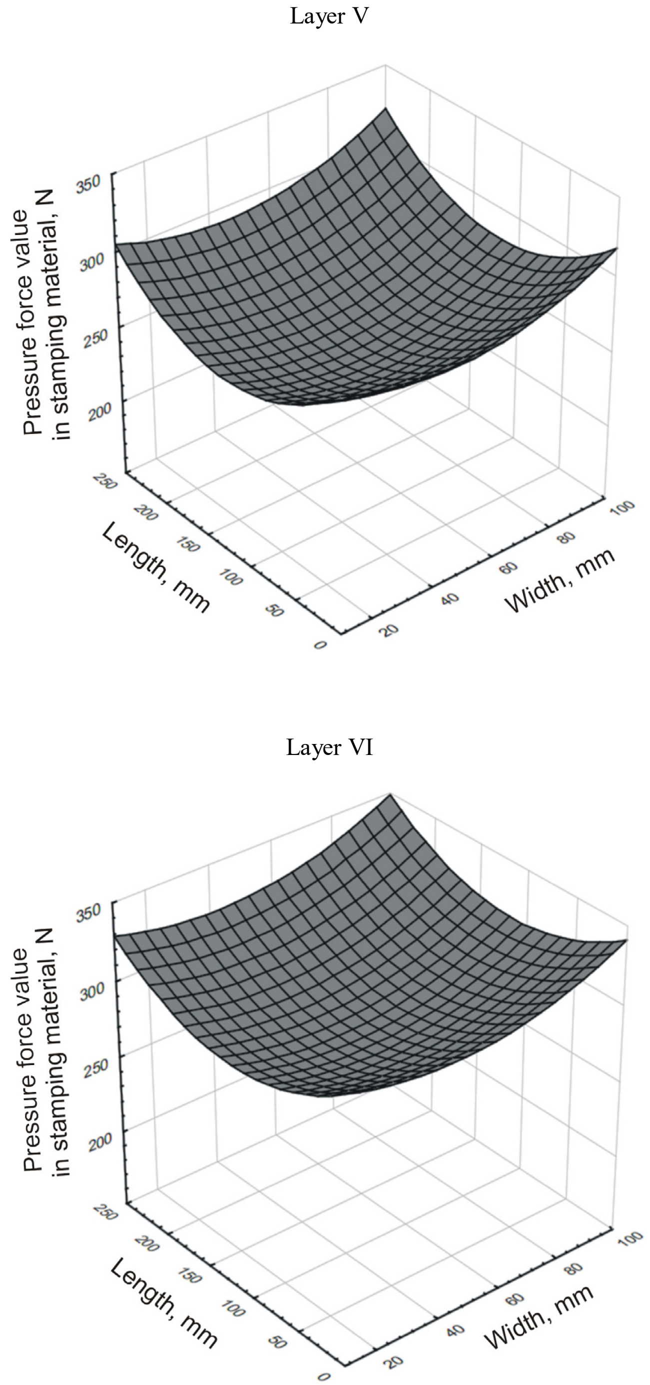


Fig. 12. Distribution of values of the unit pressure force on matrix grains in Layers V and VI of the stamping

4. Conclusions

The obtained results indicate that the largest values of the unit pressure force occur in the mass areas reproducing corners and side walls of stampings.

Lower pressure forces occurred in central regions of stampings. This difference will result in uneven distribution of material density within the stamping volume. The nature of density differences within volume of stampings will be the same as this of the pressure force unevenness.

The experiment with lead balls allowed to determine only the forces acting in the direction of punch movements. Their values were significantly higher than those of force components oriented towards die inserts which are decisive for their wear and tear. To determine values of these forces it would be necessary to perform an additional experiment, involving e.g. recording of the normal pressure force with the use of sensors mounted on surfaces of replaceable die inserts.

Acknowledgement

The study presented in this paper was carried out in the framework of project entitled INNOVATIVE TECHNOLOGICAL PROCESS OF MANUFACTURING MOULDS FOR PRODUCTION OF REFRACTORY MATERIALS co-funded from Operational Programme Innovative Economy, Measure 1.4-4.1 Support for goal-oriented projects and support for implementation of results of R&D works.