DOI: 10.31897/PMI.2019.2.216

UDC 621.762.824

DEVELOPMENT AND RESEARCH OF FORMATION TECHNOLOGIES ON SPECIALIZED PRESSES WITH SUBSEQUENT SINTERING OF HIGH-DENSITY DETAILS FROM IRON-BASED POWDERS

Aleksandr M. DMITRIEV, Nataliya V. KOROBOVA, Ashot Zh. BADALYAN
Moscow State Technological University «STANKIN», Moscow, Russia

Creating shifts of the lyaers in a deforming workpieces improves the quality of the product produced by pressure treatment. qual-channel angular pressing and precipitations of a cylindrical billet with a rotating turnaround were developed by specialists earlier and became basic for scientists engaged in nanotechnology. One of the most modern schemes for creating nanostructures by processing on presses is the «Cyclic Extrusion Compression» scheme (in Russia – «Hourglass»), which has significant drawbacks. To date, research on the creation of layer shifts in compacted metal powders is substantially less than in compaction of compact blanks. The article developed compaction schemes for presses of blanks from iron-based powders that have a certain analogy with the «Hourglass», while lacking the disadvantages inherent in the named scheme and implemented on the created samples of specialized hydraulic presses. The results of the studies of density, strength and microhardness before sintering the samples molded from a number of domestic and imported powders on iron base, including those doped with carbon and other alloying components, are described.

It has been established that with the use of the formation schemes for powders providing large shifts between particles, the density of the preforms increases on average by 10-12 %. With an average stress (16.32 MPa) of the transverse section of the molded specimen prior to its sintering, molding with shifts between particles increases this stress by 78 %. The strength after sintering of samples made using the compaction schemes developed by the authors of the article increases approximately by 2 times. Magnetic pulse treatment (MPT) of a molded sample prior to its sintering increases its resistance to shearing before sintering, regardless of the molding pattern. When MPT of both the powder and the molded sample is executed, the most uniform distribution of microhardness in the sample is achieved, and after subsequent sintering, the most uniform distribution of the mechanical characteristics of the product.

The results of all studies are described by regression equations.

Keywords: powder materials; iron base; cold molding on presses; shifts shaping; high-density samples; mechanical characteristics of the samples before sintering; Influencing magnetic pulse processing during molding; study

How to cite this article: Dmitriev A.M., Korobova N.V., Badalyan A.Zh. Development and Research of Formation Technologies on Specialized Presses with Subsequent Sintering of High-density Details from Iron-based Powders. Journal of Mining Institute. 2019. Vol. 236, p. 216-228. DOI: 10.31897/PMI.2019.2.216

Introduction. The creation in the deformable workpiece shifts of its layers is always associated with changes in the structure of the material and, as a consequence, the quality of the manufactured product.

In developing new technological processes, in the early 1980s, scientists in the field of plastic deformation of workpieces, V.M.Segal and O.A.Ganago, published two main schemes for plastic deformation of workpieces, which in subsequent publications of domestic and foreign scientists were called «intensive plastic deformation» (IPD).

Such implemented on the presses, the IPD schemes are the following.

The first scheme is equal channel angular (ECA) pressing, the analysis of which was performed in the works of V.M.Segal and his followers [6, 16].

In [23, 24], the study of the flow of material during ECA pressing with the use of flow lines, to which the directions of shear strain rates are tangent, was carried out. It is believed that if these velocities are equal along two mutually perpendicular directions corresponding to the flow lines, then the net shift scheme is realized, and if not, the simple shift scheme. As a rule, the flow of material can be described by superposition of pure and simple shifts.

In addition to the analysis of the ECA-pressing, V.M.Segal in his works paid attention to the engineering problems of the implementation of the ECA-pressing scheme, in particular, the creation of the stamping schemes, in which the mobile tooling elements are provided. They move to change

DOI: 10.31897/PMI.2019.2.216

the contact friction conditions between the workpiece and the tool and thus affect the deformation of the workpiece [21].

IPD torsion with open strikes, which is an industrial development of the Bridgman anvil method, is described in the works of O.A.Ganago [8].

At present, this scheme is successfully applied to various metallic materials [10, 18].

The third scheme «Cyclic Extrusion Compression (CEC)» was proposed later by J.Richert and M.Richert [1]. In Russia, this method of processing workpieces received the name «Hourglass» [2]. The Russian name reflects the processing scheme so precisely that it can be imagined even without a picture. The matrix in which the deformable workpiece is placed has the shape of a working cavity, similar to the shape of an hourglass flask. After pushing half the length of the workpiece through the middle part of the die cavity, narrowed as compared with the side parts having the same diameters, the pressure is applied to the ends of the workpiece by counter-displacement of the punches. Under pressure from the side of the punches, the billet is precipitated, and its material fills the gaps of the die without a gap. At the next stage, the traverse with the matrix fixed on it, the cavity of which has the described form, performs reciprocating movements with fixed punches, the pressure on which is maintained during the processing of the workpiece. During the reciprocating motion of the matrix, the material of the workpiece is squeezed through its middle constricted part from one side cavity to another, where it settles and fills the gap formed due to the difference in the diameters of the middle and side portions of the matrix cavity.

However, the three deformation schemes described have disadvantages.

During ECA-pressing, the formation of unfilled material of a dead zone adjacent to the external angle of intersection of channels is possible [25]. As a result, the source of plastic deformation changes from an ideal shear plane with a simple shear to a large volume area with several shear planes. Backpressure is required to fill the dead zone. Under the action of counter-pressure, the site of plastic deformation is localized into a single shear plane, typical of an absolutely plastic solid. However, the need to create back pressure significantly complicates the design used for the deformation of the material of the stamp or press.

The die patterns proposed in [21], in which movable elements are provided for changing the conditions of contact friction between the workpiece and the tool, are far from their practical implementation.

In the case of IPD torsion, as indicated in [14], the samples were subjected to torsion under the applied pressures (1-9 GPa). It was found that the pressure on the end of the sample significantly affects the change in its structure.

In our opinion, it is unrealistic to carry out industrial production of parts at the specified pressures applied to the sample. This is due not only to the destruction of the tool at these extremely high pressures. The problem is that a stamp or a press that implements the rotation of the plate which is deforming the blank must necessarily contain a pair of screw – nuts with non-braking threads [7]. With an axial load on the screw that generates the above pressures, the lubricant will be squeezed out of the thread, and the contacting surfaces of the screw and nut at the end of the specimen deformation will be in conditions of «dry» friction. As a result, after the manufacture of each sample, it will be necessary to disassemble the punch in order to open the contacting surfaces of the screw-nut pair and cover them with a new lubricant.

Due to the high pressure on the tool when implementing the third deformation scheme, in work [20] such an operation was recommended to apply only to soft materials. At the same time, it is noted that high hydrostatic pressure contributes to the processing of fragile materials.

We emphasize that when applying the third of the schemes described above, the problem of the product from the matrix is not solved.

Among the works on the creation of IPD schemes, only a few of them are aimed at studying the processing of powder materials [11].

DOI: 10.31897/PMI.2019.2.216

Formulation of problem. The aim of the work is the creation of rational for practical application methods of compaction of iron-based powder materials, a method of express analysis of mechanical characteristics that is convenient in terms of parts production, as well as the construction of experimental models of mathematical models to predict the mechanical characteristics of manufactured parts.

In practice, when manufacturing parts from iron-based powder materials on presses, specialists in the field of powder metallurgy did not strive to create shifts in the material being compacted and compressed the powder mixture by axial compression in a closed matrix. They developed recommendations in which the specific force applied to the tool sealing tool, p = 600-800 MPa. The specific force is defined as the magnitude of the force compressing the workpiece P divided by the area perpendicular to the direction of the force of the section of the workpiece.

If the specific force is more than 800 MPa, then as a result of compaction of the powder, the whole billet fails. The cause of the destruction of the workpiece during its compression with a specific force of more than 800 MPa is the resistance to compression from the macropores present in the powder. Under the action of the applied force, cracks are generated on the surfaces of the macropores. With a further increase in strength, these cracks grow and the workpiece collapses.

When the specific force of axial compression is not more than 800 MPa, the billet has a residual porosity of 15-18 %. Due to residual porosity in the billet, after sintering, they do not receive a set of mechanical characteristics: high strength and ductility.

With such a residual porosity, the dopants after heat treatment also have practically no effect on the mechanical characteristics of the manufactured part.

Alloying additives in the form of powders of other metals contribute to the powder mixture – a mixture of basic iron powder with zinc stearate powder, acting as a lubricant. The components are mixed in special mixers.

After forming the blanks, a batch of powder parts is subjected to sintering in a methodical furnace with a reducing atmosphere. As a result of sintering, the alloyed powder mixture turns into powder steel.

Solution Description. The authors of the article have developed schemes for manufacturing high-density parts from iron-based powder materials. In accordance with these schemes, shifts of layers are created in the material being compacted, which leads to the closure of the macropores in the workpiece to be sealed and allows for compaction with the value of the specific force on the tool, limited only by the fatigue tool resistance. In this formulation, the problem is not about the strength of the tool, but about its resistance to fatigue, since the research results are intended for their practical implementation in the large-scale production of machine parts.

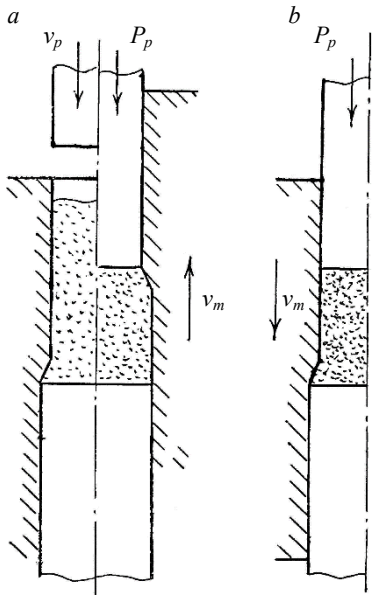

Fig.1. Schemes of forming the billet powder axial compression with the creation of shifts of the layers of material

Designed by the authors of the scheme for forming blanks are shown in Figure 1.

The first (I) scheme is the formation of a sample by the movement of a punching stamp with a speed v_p with a simultaneous increase in the diameter of the sample as it moves from the upper cylindrical cavity of a matrix with a smaller diameter to the lower cylindrical cavity with a larger diameter (Fig.1, *a*). The specified movement is carried out by moving the matrix in the direction of the vector v_m. When this occurs, layered radial extrusion of the sample material into the opening cavity of the matrix.

The second (II) scheme is the same operation as in the first one. Then, while saving the force P_p from the side of the punch, extruding the sample from the cavity of the matrix of larger diameter into the cavity of a smaller one, carried out by moving the matrix (Fig.1, *b*) in the direction of the vector v_m.

Changing the shape of the workpiece during pressure treatment is always associated with shifts in the material. Shifts are created both when forming a powder using the I scheme of its compaction, and II scheme.

DOI: 10.31897/ PMI.2019.2.216

When molding according to the described schemes, an average density of parts of 90 % or more is achieved.

As a result, it is possible to carry out milling of the molded workpiece prior to its sintering, and grind on its meridional surface. This is an achievement in powder metallurgy, since it makes it possible to examine in the microscope not only the initial powder charge and the structure of powder samples after sintering, but also the structure of the molded preform before sintering it.

In the article, the achievable mechanical characteristics of the samples manufactured according to the schemes shown in Fig. 1 were investigated, depending on the grade of the powder material and the specific force that was applied to the sample. As for the structure of the molded samples, the possibility of establishing the correlation of their structure with mechanical characteristics was shown in [12]. In our article, the task of identifying such a correlation is not posed.

The authors of the article [4] presented an analytical study of the values of accumulated deformations when grinding the grains of powder blanks by processing them using compaction schemes (Fig.1). This article focuses on measuring indicators of hardness and strength of fabricated samples before sintering, which was not previously carried out due to insufficient sample density, as well as describing changes in these indicators by regression equations.

Research methods, equipment. To implement the scheme of forming the powder billet by axial compression with the creation of shifts of its layers, the design of specialized presses developed by the authors [5, 9] are used (Fig.2).

In the press, the matrix installed in the traverse, with the help of side-mounted hydraulic cylinders attached to it, is forcibly moved in the direction determined by the diagram in Figure 1.

The function of the press ram is performed by the plunger of the main central hydraulic cylinder, located below the crosshead, directly on which, without a die plate, a workpiece that pushes the punch is placed. The second punch is located on a fixed support connected to the upper crossbar of the press.

The return plunger of the main hydraulic cylinder is carried out by an additional hydraulic cylinder located under the lower crossbar of the press.

Note that when compacting the powder using the schemes (Fig.1) and the press (Fig.2), the idea of active use of contact friction forces between the sample and the tool, noted above when considering work [21], is implemented. More comprehensive this problem is solved in [13].

In the study described below, the mixing of the powders was carried out in a batch mixer using the dry method. A horizontally disposed drum (rotational speed of 50 rpm) was filled with powders of 1/2-1/3 volume. In addition to powders, balls were loaded into the drum from a rolling bearing with a diameter of 15 mm. The mixing time was 1 hour. After mixing, the balls were removed from the charge.

When using the compaction method (see Figure 1), the following experiments were performed to build mathematical models that allow determining the density, strength and microhardness distribution of molded powder samples prior to sintering, as well as hardness and tensile strength of the blanks made from them after sintering.

Sintering the blanks was carried out in a reducing atmosphere. The atmosphere served as hydrogen. A passing furnace was used that had three zones: the burning zone of zinc stearate at a temperature of 600-700 °C, the sintering zone (temperature 1100 °C, exposure 1.5 hours) and cooling the sintered samples to a temperature below 600 °C. This mode in the furnace avoids cooling the samples in air with the formation of dross.

In the experiment on the molding of high-density samples, powders PZhV2.160.28, PZhRV2.200.26, PZhRV3.200.26, PZhV4.160.28 (GOST 9849-86),

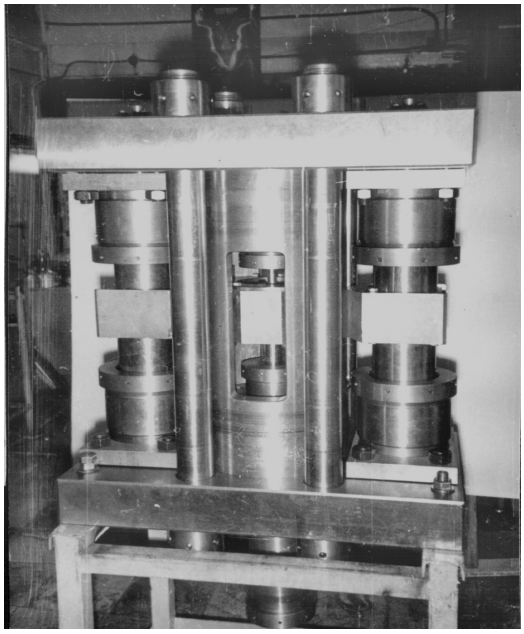

Fig.2. The press used to form the powder billet with the creation of shifts between its particles

DOI: 10.31897/ PMI.2019.2.216

WPL-200, ULTRAPAC-LE (Mannesmann Demag) were investigated. Note that the ULTRAPAC-LE powder is initially doped with the following components, %: 1.5 Cu; 4 Ni; 0.5 Mo [15].

Brand powder adopted for the factor X_1. In the conducted research, the conditional values of the factor X_1 levels were assigned to the considered powders: 0, 1, 2, 3, 4, 5 in accordance with the order in which they are written above.

In the implementation of the molding schemes (Fig.1), a matrix with cavity sections of 32 and 36 mm in diameter was used. The specific force p applied to the end of the powder billet compacted in the matrix (factor X_2) at the end of molding was 300; 340; 380; 420 MPa.

Mechanical schemes for forming samples (factor X_3) are assigned the following conventional levels: 0 – I scheme and 1 – II scheme. Zinc stearate (factor X_4) was added to the mixture in an amount of 0.5 % and 1 % by weight.

The experiment plan is selected from the catalog of V.Z.Brodsky (Table 1). As a result of the experiment according to the plan given in table. 1, mathematical models of the following type are constructed for the density of the molded samples, the Brinell hardness and the tensile strength of the blanks obtained after sintering these samples:

$$y = b_0 + \sum_{i=1}^{4} b_i X_i + \sum_{i=1}^{2} b_{ii} X_i^2 + \sum_{i=1}^{2} b_{iii} X_i^3 + b_{1111} X_1^4 + b_{11111} X_1^5, \quad (1)$$

where i – factor number; X_i – factor value; b_0, b_i, b_{ii}, b_{iii}, b_{1111}, b_{11111} – the coefficients of the mathematical model, respectively, before the free term and the factors included in the model are linear, quadratic, cubic, in the fourth and fifth degrees.

Table1

Experimental design in natural scale and the results of experiments

Experiment number	Powder brand	p, МПа	Molding pattern	Zinc Stearate Content, %	γ, g/cm^3	HB	Strength of parts $\sigma_в$, MPa	
1	2	3	4	5	6	7	8	
1	PZhV2.160.28	300	0	0.5	5.7	36.1	65	59
2	PZhRV2.200.26	340	0	1	5.77	47.4	77	71
3	PZhRV 2.200.26	380	0	0.5	5.8	46.5	94	85
4	PZhV2.160.28	420	0	1	6.4	50.4	121	119
5	PZhRV 2.200.26	420	1	0.5	7.15	67.8	211	197
6	PZhV2.160.28	380	1	1	7.25	71.6	223	213
7	PZhV2.160.28	340	1	0.5	7.05	54.5	193	187
8	PZhRV2.200.26	300	1	1	6.9	53.8	168	164
9	PZhRV3.200.26	300	0	0.5	5.8	34.6	52	48
10	PZhV4.160.28	340	0	1	5.65	30.2	42	36
11	PZhV4.160.28	380	0	0.5	5.65	31.0	52	46
12	PZhRV3.200.26	420	0	1	6.34	43.2	109	103
13	PZhV4.160.28	420	1	0.5	6.5	45.5	171	175
14	PZhRV3.200.26	380	1	1	7.15	47.8	196	188
15	PZhRV3.200.26	340	1	0.5	6.75	47.1	165	161
16	PZhV4.160.28	300	1	1	6.4	33.4	117	107
17	WPL-200	300	0	0.5	5.65	46.7	69	63
18	ULTRAPAC-LE	340	0	1	6.0	82.3	202	186
19	ULTRAPAC-LE	380	0	0.5	6.05	85.6	214	206
20	WPL-200	420	0	1	6.2	45.0	128	126
21	ULTRAPAC-LE	420	1	0.5	7.15	116.0	390	366
22	WPL-200	380	1	1	7.3	68.2	227	223
23	WPL-200	340	1	0.5	7.05	59.1	199	197
24	ULTRAPAC-LE	300	1	1	7.15	88.4	332	320

DOI: 10.31897/PMI.2019.2.216

Density was determined as the quotient from dividing the mass of a sample weighed on a laboratory scale by its volume. The volume was calculated based on measurements of the heights of the sample areas with a diameter of 32 and 36 mm.

The Brinell hardness of the blanks after sintering was measured by the standard method.

In previous works of the authors of this article, for domestic powders, the relationship between the Brinell hardness of the sintered powder billet and its tensile strength was found, described by the regression equation [9]:

$$\sigma_{в} = 5.449\,\mathrm{HB} - 192.7\,. \qquad (2)$$

For powders WPL-200 and ULTRAPAC-LE, similar dependencies are given in the prospectus of «Mannesmann Demag» company [15].

Using these dependences on the magnitude of the hardness of the sintered billet in each of the experiments was determined tensile strength.

In the second experiment in the stamp, the strength of the samples for cutting before their sintering was investigated.

To determine the fracture stress at cut τcr, two sets of knives were used, differing from each other only by the diameters of the cavities for cutting cylindrical samples: d = 36 mm – realization I of the molding scheme (Fig.1, *a*) and d = 32 mm – after molding schemes (Fig.1, *b*).

The experiments were carried out on an Instron testing machine (3.5 MN force) as follows: a stamp with workpiece 1 (Fig.3) was mounted on a fixed plate of a testing machine, the upper stamp plate with a punch 3 was lowered, force was transmitted to it through a knife 2 , and the workpiece was cut in two sections. In this case, the writing device of the machine recorded the force of the cut.

A cut in two sections is necessary, since the knife 2 has a thickness sufficient to ensure its strength and rigidity. When it was lowered from the workpiece 1, a part was cut out in the form of a «pill». The ends of the «pills» were the above two sections. In this case, the writing device of the machine recorded the force of the cut.

The shear stress on the cut surface (in megapascals) was determined by the formula $\tau_{av} = P/2S$, where P – force (maximal), κN; $2S$ – the total area of the slice of the sample in two sections, mm^2.

Since in modern technological processes they combine different physical and chemical technologies, the important tasks of modern engineering are solved by the cooperation of specialists from different scientific fields [16, 17, 19].

In this regard, among the factors influencing the compaction of the powder mixture of factors, the effect of magnetic-pulse treatment (MPT) of the material being compacted was investigated. The MPT in the formation of powder blanks by the authors of the article was used earlier [4]. However, in early studies, blanks were molded with traditional compaction in a closed matrix, without creating shifts in the compacted charge layers. In past studies revealed a significant effect of magnetic pulses, allowing to increase the density of powder blanks. Based on this experience, MPT was applied in the experiment described.

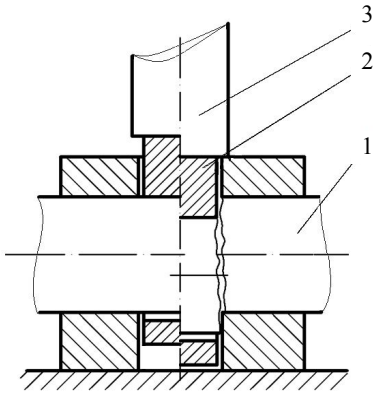

Fig.3. Stamp diagram for shear testing of green samples resistant (τcp)
1 – sample; 2 – a knife; 3 – punch

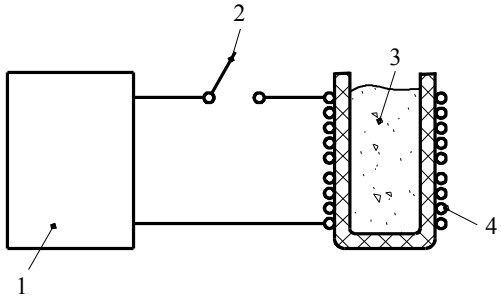

Fig.4. Magnetic pulse treatment circuit
1 – source of pulsed magnetic field;
2 – circuit closing device; 3 – powder; 4 – inductor

DOI: 10.31897/PMI.2019.2.216

The effect on the density of the molded sample of the MPT of the powder preceding its compaction, as well as the m & e of the molded sample, was evaluated. The MPT of the powder was carried out according to the scheme (Fig.4) and pursued the same goal – increasing the density of the blanks.

In our studies, the MPT of iron powder and samples was carried out on the installation «Impulse-A», created in MSTU named after N.E.Baumana.

A weighed 100 g of the powder mixture was loaded into the cassette and placed in the inductor. When locking the chain, MPT occurred. The field strength is 106 A/m and the processing time is 0.8 ms. The treated batch of the mixture was aged for 24 hours in order to level the residual stresses in the particles. Molded samples were processed with the same modes as the charge.

The study used a powder batch based on iron powder grade PZhRV3.200.28. Determined the effect on the value τ_{av} The following factors: molding scheme – X_1; the presence of MPT powder – X_2; the presence of an MPT sample – X_3; the content in the mixture of zinc stearate, % – X_4; content in the charge of carbon, % – X_5.

The authors of the article based on preliminary experiments set the form of a mathematical model:

$$y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_{12}X_1X_2 . \quad (3)$$

When varying the deformation scheme (see figure 1), scheme I was assigned the level of the factor $X_1 = 0$, and scheme II – the level of $X_1 = 1$. In the presence of the MPT of the charge $X_2 = 0$, in the absence – $X_2 = 1$. In the presence of the MPT of sample $X_3 = 0$, in the absence of – $X_3 = 1$. The factor X_4 was varied at levels of 1 % by weight and 0.5 %. Factor X_5 was varied at levels of 0 % and 0.6 % by weight.

The experiments were carried out according to the experimental plan given in columns 2-6 of Table 2 and duplicated for the subsequent statistical analysis of the results. The experiment plan is selected from the catalog of V.Z.Brodsky.

Table 2

The experiment plan and the results of experiments on measurements of τ_{av}

Experiment number	X_1	X_2	X_3	X_4, %	X_5, %	τ_{av}, MPa
1	2	3	4	5	6	7
1	0	1	1	1	0	19.2
2	1	1	1	0.5	0.6	26.8
3	0	0	1	0.5	0	17.7
4	1	0	1	1	0.6	30.0
5	0	1	0	1	0.6	13.8
6	1	1	0	0.5	0	28.9
7	0	0	0	0.5	0.6	13.2
8	1	0	0	1	0	29.3

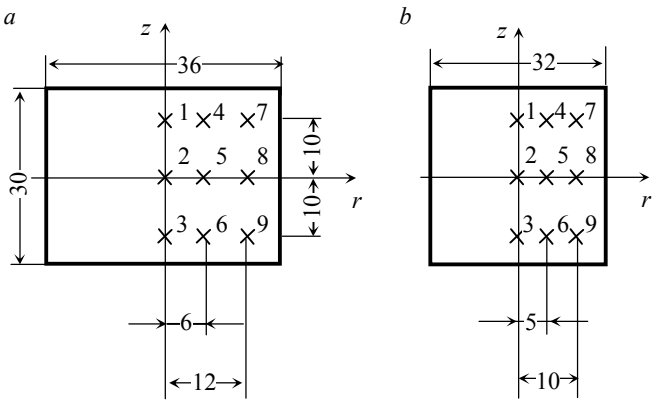

Fig.5. The scheme of breakdown of the meridional sections of the blanks into areas: for deforming according to I scheme (*a*); for deformation according to II scheme (*b*)

In the third experiment, the microhardness distribution (H_{100}) was studied in powder-shaped blanks that were molded with shears.

Powder charge on the basis of PZhRV3.200.26 was used in two states: without MPT and after MPT. The blanks were molded according to two schemes (see Fig.1).

Before the molded blanks, before their sintering, microhardness was measured at their meridional section.

The area of the plane of the meridional section of the workpiece was divided into 9 areas (Fig.5).

DOI: 10.31897/ PMI.2019.2.216

On the basis of the conducted preliminary experiments, the following form of the mathematical model is given:

$$H_{100} = b_0 + b_{11}X_1^2 + b_{22}X_2^2 + b_1X_1 + b_2X_2 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 . \quad (4)$$

In the experiment, the center coordinate of each area numbered in Fig.5 was radially related to the diameter of the molded sample (factor X_1) varied at levels: 0; 0.33; 0.66. The coordinate of the center of each area numbered in Fig. 5 in height, referred to the diameter of the molded sample (factor X_2), was varied at levels: –0.6; 0; +0.6. When varying the deformation scheme, scheme I was assigned the level of the factor $X_3 = 0$, and scheme II – $X_3 = 1$. In the presence of the MPT of the charge $X_4 = 0$, in the absence of the MPT of the mixture $X_4 = 1$. In the presence of the MPT of the charge $X_5 = 0$, in the absence – $X_5 = 1$.

The experiments were carried out according to the plan given in columns 2-6 of Table 3. The experiment plan is chosen from the catalog of V.Z.Brodsky.

Table 3

Experimental plan and results of experiments on microhardness measurements H_{100}

Experiment number	X_1	X_2	X_3	X_4	X_5	Experiment double number	Microhardness H_{100} (y)	$\bar{y}_u$	y_m
1	2	3	4	5	6	7	8	9	10
1	0	–0.6	0	0	0	1	99.85	99.85	99.2
						2	99.85		
						3	99.85		
2	0.33	0	0	1	0	1	92.72	94.17	94.48
						2	95.64		
						3	94.46		
3	0.66	0.6	1	0	0	1	84.13	84.14	85.3
						2	85.31		
						3	82.98		
4	0.33	0.6	0	0	0	1	109.47	103.7	100.5
						2	97.18		
						3	104.44		
5	0.66	–0.6	0	1	0	1	99.85	96.6	96.8
						2	99.85		
						3	89.96		
6	0	0	1	0	0	1	98.76	104.6	103.1
						2	107.53		
						3	105.36		
7	0.66	0	0	0	1	1	105.36	99.01	96.5
						2	95.6		
						3	96.08		
8	0	0.6	0	1	1	1	115.18	105.5	109.37
						2	99.85		
						3	101.52		
9	0.33	–0.6	1	0	1	1	99.85	99.85	101.9
						2	99.85		
						3	99.85		

The purpose of creating a mathematical model is to calculate the microhardness values on it at any point of the molded workpiece, although only 9 experiments were carried out to build this model (with three repetitions each).

Microhardness measurements were carried out using a PMT-3 instrument in accordance with GOST 9450-76 with uniform duplication ($n = 3$) in each experiment.

Mathematical models (1), (3), (4) are written in general form. Based on the results of experiments in the implementation of plans for experiments (Table 1, 3, 5) calculated their coefficients. Note that the use of a simple formula for calculating the coefficients is possible only if the matrices of the experimental plans given in Tables 1, 3 and 5 were translated into a coded scale in which they meet the conditions of symmetry and orthogonality.

After calculating the coefficients in this coded scale, a statistical analysis of the models was performed. As a result of statistical analysis, the significance of the calculated coefficients was estimated (with a confidence level of 95 %), and the terms with coefficients whose significance was not confirmed were excluded from the models. This explains the absence of a part of the members in the models given below as compared with the models (1), (3) and (4).

DOI: 10.31897/PMI.2019.2.216

Checking the adequacy of all the models below was carried out using Fisher criterion (with a confidence level of 95 %). The audit showed that there is no basis for not accepting the hypothesis of the adequacy of one of these models.

After the described statistical analysis, the given mathematical models were returned to the scale in which the initial models (1), (3) and (4) are given.

Research results. When factors were combined for each experiment given by the experiment plan (see Table 1), two samples were formed. The densities given in column 6 of Table 1 are average for two samples.

By processing the results of experiments obtained the following model equation for the density (in grams per cubic centimeter) manufactured samples:

$$\gamma = 4.7 - 2.38X_1 + 0.0031X_2 + 1.66X_3 + 0.368X_4 + \\ + 3.95X_1^2 - 2.303X_1^3 + 0.5447X_1^4 - 0.04455X_1^5. \quad (5)$$

When analyzing the model (5), in order to reveal the effect of the powder grade for the values assigned to the powders (X_1), the values of A:

$$A = -2.38X_1 + 3.95X_1^2 - 2.303X_1^3 + 0.547X_1^4 - 0.04455X_1^5.$$

The calculation results are as follows. For powder PZhV2.160.28 $A = 0$, for ПЖРВ2.200.26 $A = -0.233$, for PZhRV3.200.26 $A = -0.094$, for PZhV4.160.28 $A = -0.476$, for WPL-200 $A = 0.112$, for ULTRAPAC-LE $A = 0.194$.

Thus, the highest density under other equal conditions is achieved with the ULTRAPAC-LE powder, the lowest – with the PZhV4.160.28 powder.

Analysis of model (5) also shows that the force at the end of the powder billet (factor X_2) affects linearly its density, since the significance of the coefficients b_{22} and b_{222} [(see formula (1)] was not confirmed. The greatest influence on the density of the sample is molding in accordance with Fig.1.

The density of the sample is significantly affected by the content of zinc stearate in the charge: about the same as the specific compressive force.

The values of hardness for each experiment are given in column 7 of table 1.

The hardness values are given in Table 1 are average for two blanks. At the same time, for each blank, the hardness was measured three times at each of the ends and an average of six measurements was found.

Model equation for hardness of fabricated samples:

$$HB = 271.3 - 0.486X_1 - 2.24X_2 + 14.52X_3 + 11.06X_1^2 + \\ + 0.0069X_2^2 - 13.65X_1^3 - 0.0000066X_2^3 + 4.26X_1^4 - 0.38X_1^5. \quad (6)$$

The resulting equation shows that the content of zinc stearate in the mixture does not affect the hardness of the sintered billet, because the significance of the coefficient in front of X_4 was not confirmed. Zinc stearate burns out at the stage of sintering the sample in the first zone of a continuous furnace.

The strength of the blank in each of the experiments using formula (2) was determined by its strength. The results are shown in column 8 of the Table 1 in accordance with the numbers of experiments.

For each experiment in column 8 of Table 1 two strength values are given, since in each experiment two samples were made.

The equation of the model for the strength of the manufactured blanks (in megapascals):

$$\sigma_в = 1115.31 - 138.31X_1 - 9.474X_2 + 112.83X_3 + 12X_4 + 236.75X_1^2 + \\ + 0.0264X_2^2 - 144.1545X_1^3 - 0.000023X_2^3 + 34.45X_1^4 - 2.754X_1^5. \quad (7)$$

The effect of the type of powder on the strength of the part for the conditional X_1 levels assigned to the powders can be determined by the formula

$$B = -138.31X_1 + 236.75X_1^2 - 144.1545X_1^3 + 34.45X_1^4 - 2.754X_1^5.$$

DOI: 10.31897/ PMI.2019.2.216

The calculation results are as follows. For powder PZhV2.160.28 $B = 0$, for PZhRB2.200.26 $B = -14$, for PZHRV3.200.26 $B = -19.9$, for PZhV4.160.28 $V = -55.5$, for WPL-200 $B = 6.64$, for ULTRAPAC-LE $B = 129.45$.

The calculation results show that the greatest strength under the other equal conditions is achieved with ULTRAPAC-LE powder, and the smallest – with PZhV4.160.28 powder.

Figure 6 shows the graphs of the density of samples formed according to the I scheme (see Fig.1, *a*), the hardness and strength of the blanks after sintering these samples. The graphs are constructed depending on the specific forces applied to the ends of the moldable samples, with 1 % content of zinc stearate in the mixture.

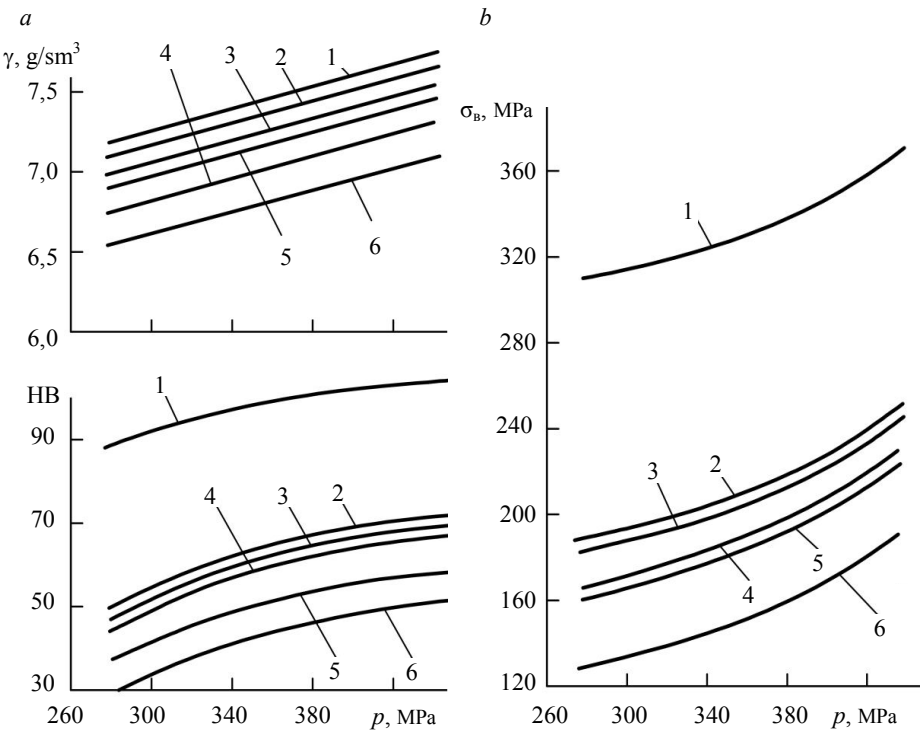

Fig.6. The dependences of the density γ of samples made according to the I scheme, hardness HB (*a*) and the strength of the blanks (after sintering the samples) (*b*) from the specific forces *p* sample molding

1 – ULTRAPAC-LE powder; 2 – powder WPL-200; 3 – PZhV2.160.28; 4 – PZhRV2.200.26; 5 – PZhRV3.200.26; 6 – PZHV4.160.28

The hardness and strength of the billets are most dependent on the brand of powder: the ULTRAPAC-LE alloy powder has a significant advantage over undoped powders, but the molding pattern (Fig.1) also makes a significant contribution, changing the attained strength by an average of 50 %.

With the same shaping forces, the density of samples from ULTRAPAC-LE powder is higher than the density of samples from PZhV2.160.28 and WPL-200 powders. The density of the latter is 6–7 % higher than the density of samples from powder PZhV4.160.28 and 2-3 % higher than the density of samples from powders PZhRV2.200.26 and PZhRV3.200.26.

The strength of the blanks from ULTRAPAC-LE powder is 2-2.4 times, respectively, and 1.5-1.7 times higher than the strength of blanks from PZhV4.160.28 and PZhV2.160.28. Billet powder PZhV2.160.28 slightly inferior in strength blanks from WPL-200. Their strength is greater than 6-10 % strength of blanks from PZhRV2.200.26 and PZhRV3.200.26.

The curves shown in fig. 6, allow to recalculate the results of research on the formation of blanks from the powder of the same brand to other brands of iron powders. From the graphs one can see the constancy of the distances between the curves and the angles of inclination of the tangents to them, regardless of the specific forming force. Consequently, the change in density, hardness and strength of the powder billet, associated with the replacement of the brand of powder, does not depend on the strength of the molding.

The results of experiments on the measurement of strength, determined by the shear test (see Fig.3) of the molded green billets, are given in column 7 of Table 2.

The equation of the model for durability when testing manufactured green samples for shear is

$$\tau_{av} = 16.32 - 12.78X_1 + 212X_3 - 4.7X_5. \quad (8)$$

The analysis of the obtained model allowed us to make the following conclusion.

DOI: 10.31897/ PMI.2019.2.216

A strong influence of the sample formation pattern (X1) on its strength was established. So, with an average value τ_{av} = 16.32 MPa the molding pattern changes this tension by 12.78 MPa.

The effect of MPT of powder batch on τ_{av} molded sample is insignificant. At the same time, the MPT of sample increases τ_{av} regardless of the molding pattern. is due to the fact that the IOI levels the residual stresses in the sample to some average value.

Increasing the amount of carbon in the charge reduces τ_{av}. This can be explained by the fact that having a lamellar structure of carbon powder, distributed between the grains of iron powder, when cut under the action of shear stresses, contributes to the beginning of the sliding of the parts of the sample relative to each other.

Note that the above-noted effect of carbon content in the charge is characteristic only when testing samples that have not been subjected to sintering. In the sintering process, carbon interacts with particles of iron powder, carrying out its doping.

The results of microhardness measurements with threefold duplication in each of the experiments are given in columns 8 and 9 of the Table. 3

After processing the results of experiments obtained the following equation for the distribution of microhardness in molded samples:

$$y_m = 102.865 + 59.23X_1^2 - 18.47X_2^2 - 32.211X_1 - 0.813X_2 + 2.124X_3 - 3.2X_4 + 0.93X_5 . \quad (9)$$

The purpose of creating a mathematical model is the possibility of calculating the microhardness values at it at any point of a molded workpiece, although only 9 experiments were carried out to build this model (with three repetitions each).

The choice at the planning stage of an experiment of the form (4) of a mathematical model (in particular, the extent to which factors are included in this model, the absence of members describing the mutual influence of factors) was quite successful: despite the small number of members of this model and, accordingly, a total of 9 experiments to determine the numerical values of the coefficients, the data in column 9 of the Table. 3 (experimentally obtained) and column 10 (calculated by model (9)) are close to each other. An analysis of the mathematical model (9) of the distribution of microhardness showed the following.

The values of microhardness along the radius of the workpiece, molded without MIO, are distributed over a certain hyperbola with maximum values of H_{100} in the center of the workpiece and along its side surfaces. In the center of the workpiece, the increase in H_{100} occurs under the action of maximum axial stresses.

In lateral surfaces, this maximum is provided by shear stresses. The minimum values of H_{100} at distances from the axis $\approx \pm$ 0.5R, where R is the radius of the workpiece. This distribution of H_{100} is explained by the fact that at the specified distances the pressure from the axial force and the tangential stresses on the side surfaces weakens.

Before the experiment, it was possible to assume that at the final stage of molding according to scheme II, the powder matrix would move down the matrix, which would create an uneven density of the workpiece and the distribution of microhardness in it in height. However, on the contrary, with the II scheme, the uniformity of the distribution of microhardness over the height of the workpiece is higher than with the I scheme, which is one of the advantages of the II molding scheme. Also, with the II scheme, the values of H_{100} increase, since deformations accumulate in the particles and their hardening occurs as compared with the I scheme, which affects the increase in H_{100}.

The MPT of the powder aligns the H_{100} indices along the radius and height of the workpiece, both with I and II molding schemes. With the MPT of a molded sample, the distribution of hardness over its meridional cross-section during the molding according to the II scheme is the same uniform as with the II scheme with the MPT powder. However, the values of hardness are higher than with MPT powder. When executing MPT of both powder and moldable preform, the most uniform distribution of microhardness is observed in the sample.

DOI: 10.31897/ PMI.2019.2.216

Conclusion. Studies have shown that, regardless of the brand of powder, to achieve high density, hardness and strength of the finished parts, it is advisable to use powder blend forming schemes, which provide for large shifts between particles, while the density of the blanks increases by an average of 10-12 %, and strength – about 2 times.

The strong effect of the shifts between particles during molding on the resistance of the green sample to the shear was established. Thus, with an average value of the cross-sectional stress of the sample of 16.32 MPa, molding with shifts between particles changes this stress by 12.78 MPa, i.e. by 78 %. Such an increase in the shear strength of the sample prior to its sintering (by express analysis) indirectly indicates an increase in its strength after the sintering operation. The increase in strength (in combination with the increase in plasticity) will be even more significant if there are components in the mixture that alloy the iron base powder and create powder steel after sintering.

Magnetic pulse treatment of a molded sample before sintering increases its shear strength, regardless of the molding pattern. The increase in strength is due to the fact that the MPT aligns the residual stresses in the sample to some average value. The equalization of residual stresses in the green sample contributes to the improvement of the conditions for its subsequent sintering.

The values of microhardness along the radius of the sample prior to its sintering, molded without m & e, are distributed over the hyperbola with the maximum values in the center of the workpiece and along its side surface.

Conducting the MPT of the powder aligns the microhardness along the radius and height of the sample before sintering. When conducting MPT of both the powder and the molded sample, the most uniform distribution of microhardness in the sample is achieved, which, after subsequent sintering, will lead to the most uniform distribution of the mechanical characteristics of the product.

REFERENCES

1. Valiev R.Z., Aleksandrov I.V. Bulk nanostructured metallic materials: production, structure and properties. Moscow: Akademkniga, 2007, p. 398 (in Russian).

2. Greshnov V.M., Golubev O.V., Rtishchev A.V. New technological scheme of pressing metals. *Kuznechno-shtampovochnoe proizvodstvo*. 1997. N 2 , p. 8-12 (in Russian).

3. Dmitriev A.M., Stupnikov V.P. Increasing the density of powder blanks during molding on presses. *Kuznechno-shtampovochnoe proizvodstvo*. 2001. N 1, p. 24-28 (in Russian).

4. Korobova N.V., Dmitriev A.M. Determination of the accumulated deformations during the grinding of the grains of powder blanks by pressure treatment. *Metalloobrabotka*. 2008. N 6 (48), p. 44-49 (in Russian).

5. Dmitriev A.M., Korobova N.V., Tolmachev N.S., Aksenenko A.Yu. Domestic development and solution of the problem of stamping hollow cylindrical parts that have a conical bottom area. *Izvestiya Tul'skogo gosudar-stvennogo universiteta. Tekhnicheskie nauki*. Iss. 10: v 2 ch. Ch. 2. 2014, p. 3-18 (in Russian).

6. Segal V.M., Reznikov V.I., Kopylov I.I., Pavlik D.A., Malyshev V.F. Processes of plastic structuring of metals. Minsk: Navuka i tekhnika, 1994, p. 232 (in Russian).

7. Stepanov B.A. Specialized equipment for stamping axisymmetric large-sized forgings. *Tekhnologiya metallov*. 2012. N 1, p. 41-45 (in Russian).

8. Subich V.N., Ganago O.A., Stepanov B.A. Punching of forgings of thin-walled disks with upsetting rotating tool. *Kuznechno-shtampovochnoe proizvodstvo*. 1981. N 6, p. 31-34 (in Russian).

9. Dal'skii A.M., Barsukova T.M., Vyazov A.F., Gavrilyuk V.S., Dmitriev A.M. et al. Technology of construction materials. Moscow: Mashinostroenie. 2005, p. 592 (in Russian).

10. Prokoshkin S.D., Khmelevskaya I.Yu., Dobatkin S.B., Trubisyna I.B., Stolyarov V.V., Prokofiev E.A. Alloy Composition, Deformation Temperature, Pressure and Post-Deformation Annealing Effects in Severely Deformed Ti-Ni Based Shape Memory Alloys. *Acta Materialia*. 2005. Vol. 53. N 9, p. 2703-2714.

11. Senkov O.N., Senkova S.V., Scott J.M., Miracle D.B. Compaction of Amorphous Aluminum Alloy Powder by Direct Extrusion and Equal Channel Angular Extrusion. *Materials Science and Engineering*: A. 2005. Vol. 393. N 1-2, p. 12-21.

12. Gubicza J., Chinh N.Q., La′ba′r J.L., Hegedus Z., Dobatkin S., Langdon T.G. Correlanion between microstructure and mechanical properties of severely deformed metals. *Journal of Alloys and Compounds*. 2009. Vol. 483. N 1-2, p. 271-274.

13. Dmitriev A.M., Korobova N.V. Expanding of Application of Cold Die Forging by Inducing Active Contact Friction Forces. *Journal of Friction and Wear*. 2013. Vol. 34. N 3, p. 232-237.

14. Zhilyaev A.P., Baro′ M.D., Nurislamova G.V., Kim B.-K., Szpunar J.A., Landon T.G. Experimental Parameters Influencing Grain Refinement and Microstructural Evolution during High-Pressure Torsion. *Acta Materialia*. 2003. Vol. 51. N 3, p. 753-765.

15. Iron and Steel Powders for Sintered Components / Höganäs. URL: https//www.hoganas.com/pmc (date of access 15.09.2018).

16. Macsarov V.V., Olt J. Managing the Process of Chip Formation by Preliminary Local Action on the Worcable Surface of the Worcpiece. *Journal of Mechanical Engineering*. 2008. N 6, p. 45-49.

17. Madissoo M., Rassner A., Maksarov V. Testing of the External Tool Holder Equipped with Alternate in its Construction. *Material Science*. 2015. Vol. 21. N 3, p. 391-395.

18. Senkov O.N., Froes F.N., Stolyarov V.V., Valiev R.Z., Liu J. Microstructure of Aluminium-Iron Subjected to Severe Plastic Deformation. *Scripta Materialia*. 1998. Vol. 38. N 10, p. 1511-1516.

19. Olt J., Liyvapuu F., Madissoo M. Dynamic Simylation of Chip Formation in the Process of Cutting. *International Journal of Materials & Product Technology*. 2016. Vol. 53. N 1, p. 1-14.

20. Rosochowski A. Processing Metals by Severe Plastic Deformation. *Solid State Phenomena*. 2005. Vol. 101-102, p. 13-22.

21. Segal V.M. Engineering and Commertialization of Equal Channel Angular Extrusion (ECAE). *Materials Science and Engineering*: *A*. 2004. Vol. 386. N. 1-2, p. 269-276.

22. Segal V.M. Materials Processing by Simple Shear. *Material Science and Engineering*: *A*. 1995. Vol. 197. N 2, p. 157-164.

23. Segal V.M. Severe Plastic Deformation: Simple Shear Versus Pure Shear. *Materials Science and Engineering*: *A*. 2002. Vol. 338. N 1-2, p. 331-344.

24. Segal V.M. Slip Line Solution, Deformation Mode and Loading History During Equal Channel Angular Extrusion. *Materials Science and Engineering*: A. 2003. Vol. 345. N 1-2, p. 36-46.

25. Semiatin S.L., Delo D.P., Shell E.B. Effect of Material Properties and Tooling Design on Deformation and Fracture During Equal Channel Angular Extrusion. *Acta Materialia*. 2000. Vol. 48. N 8, p.1841-1851.

***Authors*: Aleksandr M. Dmitriev**, *Doctor of Engineering Sciences*, *Professor*, *Corresponding Member RAS*, *counteess.olga@gmail.com* (*Moscow State Technological University «STANKIN»*, *Moscow*, *Russia*), **Nataliya V. Korobova**, *Doctor of Engineering Sciences*, *Head of Department*, *Expert of RAS*, *mt-6@yandex.ru* (*Moscow State Technological University «STANKIN»*, *Moscow*, *Russia*), **Ashot Zh. Badalyan**, *Candidate of Engineering Sciences*, *Lecturer*, *p-ooogrin@yandex.ru* (*Moscow State Technological University «STANKIN»*, *Moscow*, *Russia*).

The paper was received on 26 March, 2018.
The paper was accepted for publication on 16 March, 2019.