Combined static-dynamic compaction of metal powder and ceramic materials

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Abstract. Combined static-dynamic compaction of powder material presents advantages for achievement of a higher degree of powder compaction for in dry conditions. One of possible realizations is the use of pulsed electromagnetic compaction (MPC) applied in addition to the static pre-compaction carried out by a hydraulic press. Experimental MPC equipment was used for compaction powders of SiC and Al-B with W fibers at different stages of grinding. The degree of compaction was evaluated by shock plate’s displacement at different levels and regimes of dynamic loading. The paper demonstrates feasibility of the method for compaction of the selected ceramic and metal powders and presents some quantitative data for practices.

1. Introduction

Compaction of ceramic powder materials is carried out by various methods: static, isostatic, vibrational, dynamic, and etc. In the static method, compaction of powder mass is performed by mechanical or hydraulic presses [1]. Usually it is not possible to obtain a sufficient density of the compacted material in the dry state. Therefore, materials with a high content of liquid component are used, commonly water content being up to 10-15% of the volume. Although a high density of compaction and a high strength of the products can be achieved by isostatic pressing [2], the possibility of manufacturing products of specified sizes and shapes is rather limited. The method of compaction of semi-dry mixtures where the liquid content is less than 5% allows the reduction of the technological cycle of products production due to decrease of pressing time. In this case dynamic compaction may be a preference.

Among the range of dynamic methods, the method of magnetic pulsed compaction (MPC) is known. The most frequently described method is a method of uniaxial compaction of powders in a rigid mold [3] and a method of uniaxial radial compaction in a thin-walled deformable electrically conductive shell [4]. The first embodiment is used for manufacturing flat articles. Material is filled into a mold and compacted by one or more shock pulses. A shock plate with a punch is driven by the energy of pulsed magnetic field induced electromagnetically. The magnitude of pulse pressure is determined by parameters of the pulsed current generator and inductor, as well as the values of electrical conductivity of the shock plate, its size and weight [5].
It should be noted that applying unilateral and single-pulse compression, the compressed product has a greater residual porosity (10–20%) and, therefore, an increased tendency to crack during sintering. A higher density can be achieved by increasing the compressive pressure. This can be achieved by increasing the operating voltage on the inductor and by increasing the pulse discharge current. However, it reduces the reliability of the equipment, especially of its working tool – the inductor. Besides, energy consumption increases. In some cases, the use of a concentrator of electromagnetic fields [6] allows increasing of the shock plate area affected by electromagnetic field and unloading of the inductor resulting in increased efficiency of the process and the endurance of the inductor. By advancement of the shock plate design, efficiency of compression also can be improved [7]. Disadvantages of the method are limitation in shape and size of the product and unevenness of properties by the product’s height. Bilateral MPC improves uniformity of the properties [8].

MPC methods are known, where compaction is done in a tubular or ring shell made of a material with high conductivity, such as copper. Two modifications are disseminated: the first one uses compressing of the shell with powder and the second one uses extension of the cell [8]. The first modification is simpler, since it uses more stable inductors installed outside the shell. The second modification (shell extension) is rational in the manufacture of thin-walled articles with the inner circular inside diameter exceeding 50 mm, since the inductor is installed inside the casing for compaction. Nevertheless, in both cases, non-uniformity of the product’s density is present due to non-uniformity of electromagnetic field along the inductor [9]. A number of methods eliminating this disadvantage was proposed [10, 11]. In recent years, interest in the use of MPC technology in powder metallurgy has increased in relation to the development of effective pulsed current generators by a number of companies in Germany [12], the USA [13], Russia [7], and China [14], as well as in connection with some new applications, in particular, for pressing nanomaterials [9, 15].

An especial interest increases in combined methods conjoining the preliminary static and the following dynamic (pulsed) compaction of materials [16]. The process of compaction of powdered material at the prior step of static compaction may be considered as the process of particles slipping relatively to each other and the deformation of particles near contact areas. With the increase of pressing force, the density of compacted products increases due to tighter packing of the particles and increase of its contact surface. Pulsed loading speeds up the mutual sliding of the particles. However, in high-speed processes of dynamic compression the air is in the pores that can impede achievement of high density [17]. It becomes obvious that for better compaction of ceramic materials it is necessary to optimize power and speed parameters of static and pulsed loading.

The work had the purpose to demonstrate that combined static and dynamic pulsed electromagnetic compaction is practical also for ceramic powders and to investigate some technological aspects of the technology.

2. Methods and materials
Investigation of compression regularities for experimental ceramic materials was performed on a specially designed complex for combined MPC which included a hydraulic press with maximal load 20 tons and a pulsed electromagnetic generator CMD-1 having the discharge power from 1 to 10 kJ and made at the experimental production workshop of the State Samara Aerospace University [7]. The principal scheme of the combined MPC method and picture of the equipment are shown in figure 1. To produce electromagnetic forces, a flat multi-turn inductor and an inductor’s unit with a shock plate, the surface of which was covered with a conductive copper layer, were designed.
Figure 1. Combined static-dynamic MPC method: A – principal scheme: 1 – hydraulic press; 2 – pulsed current generator; 3 – flat coil; 4 – shock plate with electrically conductive coating; 5 – ceramic powder in form; B – a general picture of equipment with pulsed current generator CMD-1 on the foreground and hydraulic press with MPC unit on the background; B - pressing form with shock plate on the top.

The magnetic pressure was estimated from the measured magnetic induction in the gap between the shock plate and the inductor. The layout of magnetic induction measurement is shown in figure 2 (A). The magnetic pressure was defined as:

\[ P_m = \frac{1}{2} \mu_0 \left[ R_u C_u U(t) / (n S) \right]^2, \]

where:

- \( U(t) \) is the voltage recorded by the sensor;
- \( n \) and \( S \) are the number of turns in the coil and the wire’s cross-section;
- \( R_u \) and \( C_u \) are active resistance and capacitance of the electronic integrator;
- \( \mu_0 \) is the magnetic constant.

To control movement of the punch in the MPC setup an optical measurement unit based on an optical lattice and the photometric principle was used. An infrared laser was used as a light source and a photodetector’s unit with an output to a digital oscilloscope was used for recording the signals. The speed of the shock plate was determined by graphical integration of movement waveforms.

Figure 2. Principal scheme for measurement of the inductance of electromagnetic field in the gap between inductor and shock plate (A) and shock plate’s displacement (B): 1 – pulsed current generator; 2 – inductor’s coil; 3 – inductance measurement coil; 4 – electrical matching circuit; 5 – recording device (oscilloscope); 6 - plate with electrically conductive coating; 7 – mold with powder; 8 – laser; 9 – photodetector.

Ceramic and metal powder materials for experimental compression in the combined MPC were powders on the base of silicon carbide (SiC) and aluminum-boron (Al-B) with tungsten (W) fiber additives. The raw materials were subjected to preliminary grinding using a high speed disintegrator DSL-175 with the number of turns of 6000 per a minute. Parameters of raw powders are given in table 1 and snapshots of the powders microstructure after grinding are shown in figure 3.
Table 1. Raw powder materials.

| Base materials | SiC  | Al-B$_{(1)}$ | Al-B$_{(2)}$ |
|----------------|------|--------------|--------------|
| Volumetric content, % | Si | C | Al | B | W | Al | B | W |
| 70 | 30 | 52 | 43 | 5 | 28 | 64 | 8 |
| Bulk density, $10^3$ kg/m$^3$ | 1.45 | 2.52 | 2.08 |
| Average particles size, microns | 20 | 50 | 10 |

Figure 3. Microscopic images of powder materials at magnification x200 after separation grinding in designator: A – SiC with energy 2400 kWh/T; B – Al-B$_{(1)}$ with energy 352 kWh/T; C – Al-B$_{(2)}$ with energy 2400 kWh/T.

3. Results and discussion

When performing the combined compression, the static pressure of pre-compacting $P_{st}$ plays an important role. It was found that there were zones of optimum values of $P_{st}$ for certain powders, where the displacement reached a high value and the quality of products was sufficient. For the ceramic powder materials it was within 12-20 MPa. Excess of $P_{st}$ didn’t show a significant increase in the ultimate density of the material but defects became revealed during sintering.

Figure 4. Dependence of displacement value of shock plate $h$ on the pre-compacting pressure $P_{st}$ for powders SiC and Al-B$_{(1)}$. Shaded areas denote optimum zones for $P_{st}$.

It was found that that displacement of shock plate $h$ depends also to a large extent on its mass $M$ and the parameters of the electromagnetic field. At constant values of mass $M$, the most important parameters of the electromagnetic pulse are angular frequency of the discharge current and pulse energy $W$. These parameters largely determine the displacement speed $V$ and the maximum value of pulse pressure $P_m$ at the loading (figure 5).
Figure 5. Instantaneous displacement speed of shock plate $V(A)$ and magnetic pulse pressure $P_m(B)$ during time $t$ of a single compaction act.

Based on previous studies [17], the optimal weight of shock plate was determined at 1.6 kg for the given volume of powder specimens with the compression area about $2 \text{ cm}^2$. The optimal discharge frequency was determined as 30 kHz. As can be seen in figure 5, at a constant value $P_s = 20 \text{ MPa}$, the intensity of pulsed loading also has its optimum. For each energy $W$ level of generator, the character of displacement of shock plate ($h$) remains the same (figure 6). One can discern three specific stages: acceleration of plate during first 10-15 microseconds, compression during the interval from about 15 to 50 ms and deceleration of plate movement and process of powder compression after 50 ms of pulse duration.

Figure 6. Changes of shock plate’s displacement $h$ overtime $t$ depending on stepped values of discharge energy of generator $W$: 1 - 1.5 kJ; 2 - 2.0 kJ; 3 - 2.5 kJ; 4 - 3.0 kJ, determined for powder Al-B$_{11}$.

One of the most important factor of MPC is the specific energy of pulsed loading $w$ reduced to the volume of compacted powder. Logically, the shock plate’s displacement and, consequently, the density of compacted products increases with growth of $w$. The quantitative dependences were obtained for three types of powders (figure 7).
Figure 7. Dependence of shock plate’s displacement $h$ on specific energy of pulsed loading $w$ after a single compaction act at $P_0 = \text{const}$ for 3 types of powders.

In general, increasing the number of shock pulses contributes to the densification of the material. However, this effect is noticeable only at a small number of pulses (figure 8). With a large number of pulses (>5), further compaction asymptotically lowers. Consequently, the number of pulses should be selected as a compromise between energy consumption, equipment wear and the required degree of compaction of the product.

Figure 8. Dependence of shock plate’s displacement $h$ on number of pulses $n$ of dynamic MPC at specific energy of discharge $w = 0.9 \text{ kJ/cm}^3$ and $P_0 = \text{const}$ for 3 types of powders.

4. Conclusions
1. Combined static and pulsed electromagnetic compression (combined MPC) opens up new technological possibilities to improve the efficiency of the process of pressing powdered materials. Meanwhile, it requires to equip additionally the hydraulic press by a generator of pulsed current and to modify the mold design.
2. Optimal parameters of static pre-compression and dynamic MPC should be found for each type of ceramic and metal powders.
3. Additional MPC action is effective at the number of pulses of 3-5, after which a further effect of the pulsed compaction becomes insignificant.
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