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Optimization of Production Process of Frangible Bullets Based on Bismuth Powder

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Abstract:

The article deals with the pressing process of the samples from bismuth powder, which were used in place of the bullet in order to optimize the frangible bullets manufacturing process. Cylindrical samples with a diameter of 9 mm were compacted by cold pressing in a cylindrical rigid die without sintering. Various pressing conditions (the changing of pressing force, pressing velocity and dwell time) were applied for compacting the samples. After compaction, the axial strength of the samples was tested to determine the optimal manufacturing process of the frangible bullet based on the bismuth powders.

Keywords:

bismuth, frangible bullet, green strength, green density, powder metallurgy, pressing force, pressing velocity

1. Introduction

Powder metallurgy technology is also used in manufacturing the ammunition for firearms. In the commercial frangible cartridges, the frangible bullets are made of various kinds of metal powder, e.g. Cu, Fe, W, etc., where Cu is the most widespread. These metals are less ecologically harmful than lead. However, iron and copper easily corrode in water-rich tissues, whereas copper is toxic at high concentration in the body. Furthermore, due to the lower density (compared to lead), the bullets made of Cu and Fe metal powder are disadvantageous from ballistic point of view. For the tungsten, it can easily exceed the density of the lead after compaction, but the price of the tungsten powder is significantly higher than the most common powder Cu and Fe. It is not possible to use W alone to manufacture a projectile because of its high hardness, since it would lead to excessive wear of the barrel bore and production tools [1-3]. Considering the commonly used metals, bismuth is closest to the ideal ecological and ballistic

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metal and that is why this metal has been used in the pilot research and development of frangible bullets. It satisfies very well the basic requirements for the production of frangible bullets, because:

- it has high density, which is closest to the lead density from used metals; high-density Bi ensures the very similar ballistic properties of the produced frangible projectile as in the classic bullet, whose main component (core) is made of lead,
- the price of bismuth powder is high, but still lower than the price of tungsten,
- as a non-toxic metal, bismuth is an ideal material in terms of ecological requirements for frangible bullet,
- bismuth is difficult to oxidize, therefore the rust does not appear on its surface and it does not corrode even in living water-rich tissues, neither does the bismuth powder corrode in manufacturing (atmospheric corrosion of powders reduces the cohesion of the pressed material),
- bismuth has a low melting temperature (271 °C), which facilitates the production process of projectile in the case of its sintering [4, 5].

The density of the sample after pressing (green density) and its compressive strength (green strength) are decisive in achieving the desired functional properties of the frangible bullet (the resistance when passing through the bore, the integrity of the bullet when flying to the target and the disintegration upon impact on a hard target or on different type of target). Therefore, these two characteristics are addressed in this article.

2. Experiment of Compaction of Bismuth Powder

The physical and mechanical properties of bismuth samples were verified by 9 mm diameter cylindrical samples, whose output is easier in comparison with the output from the bullets and the compressive strengths are more suitable in testing than the ogive shape bullets. To produce the samples, 100% bismuth powders (hereinafter Bi100) and a mix of metal powders Bi (50%) – Cu (50%) (hereinafter BiCu) of the total weight of 6 g were used. The samples were cold-compacted in a rigid cylindrical die with the internal diameter of $9.00^{+0.05}$ mm using a hydraulic press for the compaction. The pressing force varied in the range of 5 kN to 30 kN. With pressing force 30 kN, the samples were pressed with various pressing speed (5 mm min^{-1}, 10 mm min^{-1} and 50 mm min^{-1}) and also with various dwell time after pressing (0 s, 5 s and 20 s). To produce the samples, bismuth powder with the grains of spherical shape in a size of 100 mesh (grains less than 150 μm) was used. Copper powder is characterized by the grains of irregular shape in a size of less than 40 μm.

Before pressing, the bulk density of the powder mixture was determined by measuring the volume of the mixture in the die at zero pressing force. The average bulk density was 5 890 kg m^{-3} for Bi100 and 4 125 kg m^{-3} for BiCu. After compaction of the sample (i.e. green compact [6]), its green density was calculated from the volume and the mass of the sample.

After compaction, the samples were subjected to the test of strength in axial compression. The compressive load in the axial direction represents the real load of the frangible bullet in a weapon in the best way and it enables also to determine the normalised characteristics of the material that can be used for further development activities.

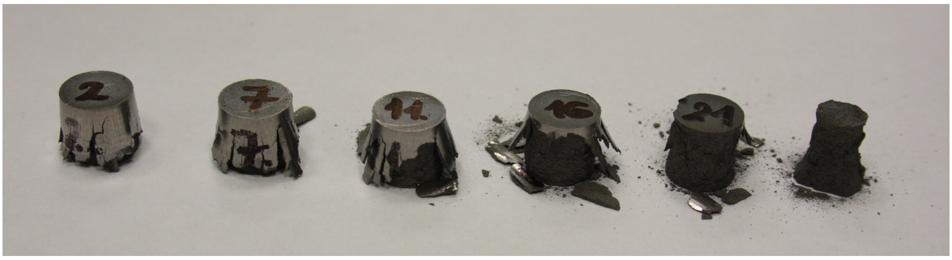

Fig. 1 Damaged samples of Bi100 after axial compression test (from the left: sample compacted with pressing force 30 kN, 25 kN, 20 kN, 15 kN, 10 kN, 5 kN)

3. Results

In the experimental results were obtained, which are further shown by the dependence of the density of the sample on the compaction pressure, and by the dependence of the compressive strength of the sample on the compaction pressure, the pressing speed and the dwell time.

3.1. Dependence of Green Density of Samples on Compaction Pressure

To clarify the influence of compaction pressure on the green density, a discrete dependence of the green density of the samples on the compaction pressure was determined, which is approximated by the exponential function (Fig. 2).

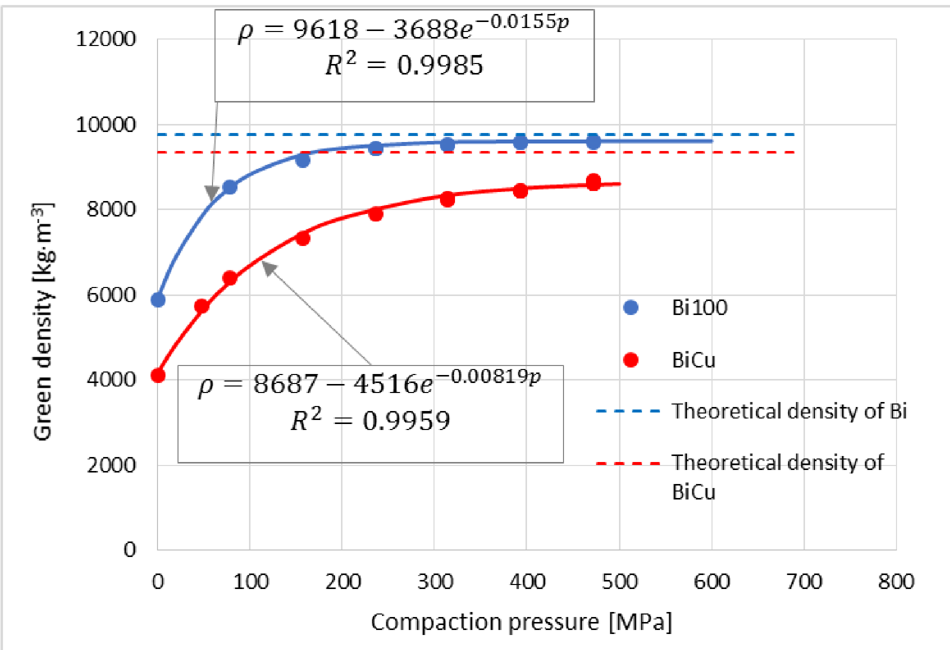

Fig. 2 Dependence of green density of samples on compaction pressure

The results show that the green density of Bi100 material is higher than BiCu at the same compaction pressure considering the low density of Cu and also due to the overall lower density of BiCu mixture. The lower green density of BiCu mixture is also given by the expansion of the sample after mold release. The mixture of BiCu is more ductile than Bi100 due to the toughness of the copper, therefore the compressibility of the BiCu mixture is better than the compressibility of pure Bi powder. Mixed BiCu powders can be a compact cylindrical sample with a diameter of 9 mm at a pressing force to 2 kN (compaction pressure of 31 MPa), while for Bi100 material, this pressing force is minimum of 3 kN (compaction pressure of 47 MPa).

The performed experiments show that the green density asymptotically approaches to the limit of almost 9 620 $kg\,m^{-3}$ for the Bi100 material and 8 690 $kg\,m^{-3}$ for the BiCu material. During pressing, with the increasing of the compaction pressure, the density of the Bi100 material increases faster than that of the BiCu material. The green density rapidly increases until the compaction pressure of 200 MPa. After that, the green density increases slowly and it is almost constant in the range of 300-400 MPa. For comparison, in Fig. 2 the value of the theoretical density (i.e. the density of pure phase composition) of 9 780 $kg\,m^{-3}$ for Bi100 is shown, which is not achievable for the samples even under the extreme compaction pressure. For the BiCu material, the green density of the sample increases slowly when increasing the compaction pressure, the green density is still increasing in the range of compaction pressure from 300 MPa up to 500 MPa.

3.2. Dependence of Ultimate Green Strength on Compaction Pressure

One of the important mechanical characteristics of the sample is green strength in compaction test, which is a critical parameter not only for ensuring the strength of the projectile when firing, but also for the other operation after pressing (e.g. handling with the projectile, sintering, assembling to cartridge).

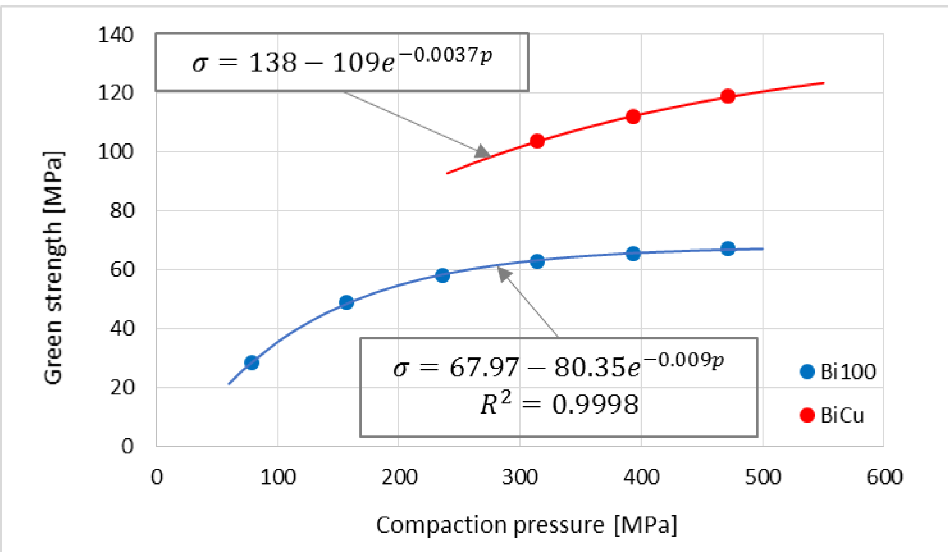

Fig. 3 Dependence of green strength of Bi100 and BiCu samples material on compaction pressure

Fig. 3 shows the experimental dependence of compressive strength on the compaction pressure for the samples made of Bi100 and BiCu; the dependence is approximated by an exponential function. As the green density, the green strength of Bi100 material increases in the initial range of compaction pressure. However, the green strength further increases in the range of compaction pressure 300-400 MPa, while the green density is almost unchanged. The pressing force is further increased, the green strength increases to a limited extent and until it reaches a maximum of 68 MPa. From Fig. 3 it is clear that the green strength of Bi100 can be effectively increased to a compaction pressure of 300-400 MPa. For the BiCu material, the green strength was tested at only 3 different pressing force (20 kN, 25 kN, 30 kN). In this range of compaction pressure, the green strength is still increasing; therefore it is possible to expect a higher green strength when increasing the pressing force. However, these compaction pressures are sufficient for the development of frangible bullet.

Although the powder mixture of BiCu has a higher compressive green strength than the powder of pure Bi, the further experiments with pure bismuth have been preferred because of the possibility of achieving a higher green density and hence a higher weight of the bullet, which is important to achieve an effect in the target, with pistol projectiles ensuring the automatic load function of the weapon. For pure bismuth bullets, the strength will be lower, thereby the conditions for disintegration of the bullet upon impact on a hard obstacle is improved. The experiments need to verify whether the achieved strength is satisfactory for their intended purpose (the integrity of the projectile during elaboration, handling with the cartridge and firing).

3.3. Dependence of Green Strength on Pressing Velocity and Dwell Time

Besides the physical and mechanical properties of the powder, the process of compaction also influences the green strength. Both pressing speed and dwell time (the time interval during which the sample is still loaded in the die with the constant compaction pressure after reaching the maximum compaction pressure) are important parameters. The higher the dwell time, the higher the green strength, since there is a decrease in internal stresses in the sample during compacting. The maximum dwell time depends on the toughness of the material; for brittle material, the dwell time is shorter than for plastic material.

Experimentally, the dependence of green strength of the sample on the pressing velocity at constant dwell time was determined. In Fig. 4, the dependence of green strength of Bi100 material on pressing velocity is shown. The samples were compacted with a pressing force of 20 kN with the dwell time of 5 s. Pressing velocity was 5 mm min^{-1}, 10 mm min^{-1} and 50 mm min^{-1}. The results show that the green strength slightly increases with increasing the pressing velocity. When increasing the pressing speed from 5 mm min^{-1} to 50 mm min^{-1}, the average value of green strength increases by 6.9% from 62.9 MPa to 67.3 MPa.

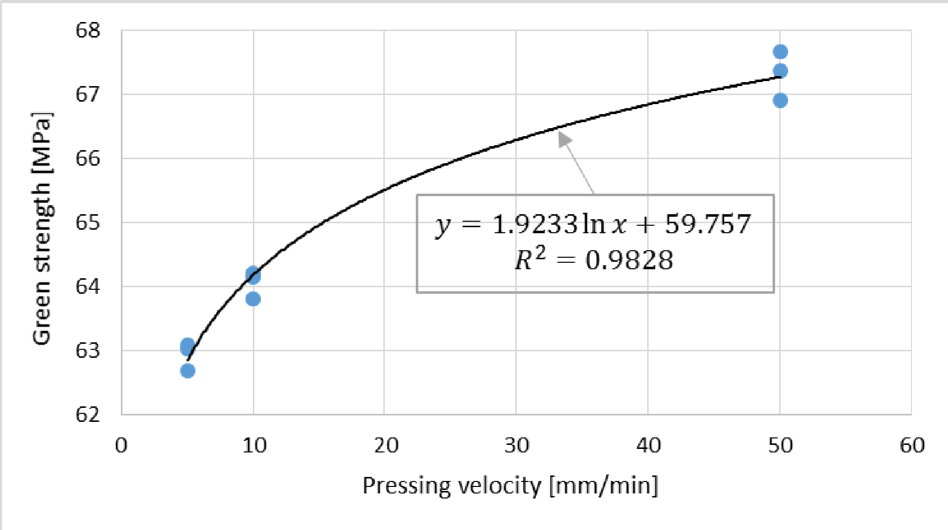

Fig. 4 Dependence of green strength of Bi100 sample on pressing velocity

In Fig. 5, the dependence of green strength on dwell time is shown. The samples were compacted with the pressing force of 20 kN and pressing velocity of 10 mm min^{-1}. The dwell time was 0 s, 5 s and 20 s. The green strength of the sample increases only slightly when extending the dwell time. When increasing the dwell time from 0 s (no dwell time) to 20 s, the average value of the green strength of the sample only increases by 2% from 63.3 MPa to 64.6 MPa.

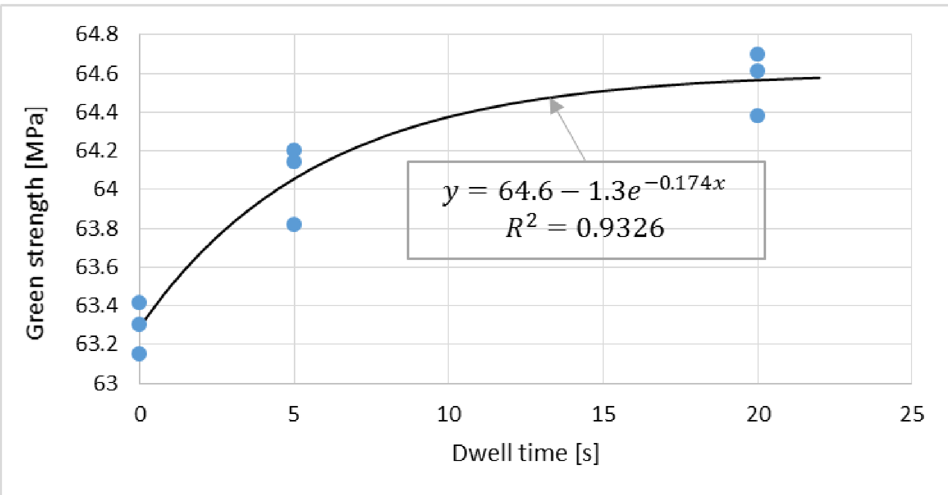

Fig. 5 Dependence of green strength of B100 sample material on dwell time

Differences in the green strength by changing the pressing process were also shown experimentally. Fig. 6 shows two different experimental results when pressing the Bi100 material. The first experiment was carried out using the universal press Zwick Z100 with the pressing velocity 10 mm min^{-1} without dwell time. The second experiment was carried out using hand press with pressing velocity about 50-70 mm min^{-1} and dwell time of 20-30 s.

The results show that the green strength of the samples produced on hand press is higher than the green strength of the samples produced on hydraulic press. Even if the approximated compaction pressure on the hand press and the blue curve shift to the right, the green strength of the samples in the first experiment would never be as high as in the second experiment. The graph shows that the sample Bi100 material can achieve a green strength of up to 75 MPa. The optimal parameters of the pressing process in the production of the samples of Bi100 material are as follows: pressing velocity of 50-70 mm min^{-1} (the higher velocity is limited by the technical possibilities of the press), the dwell time of 20-30 s.

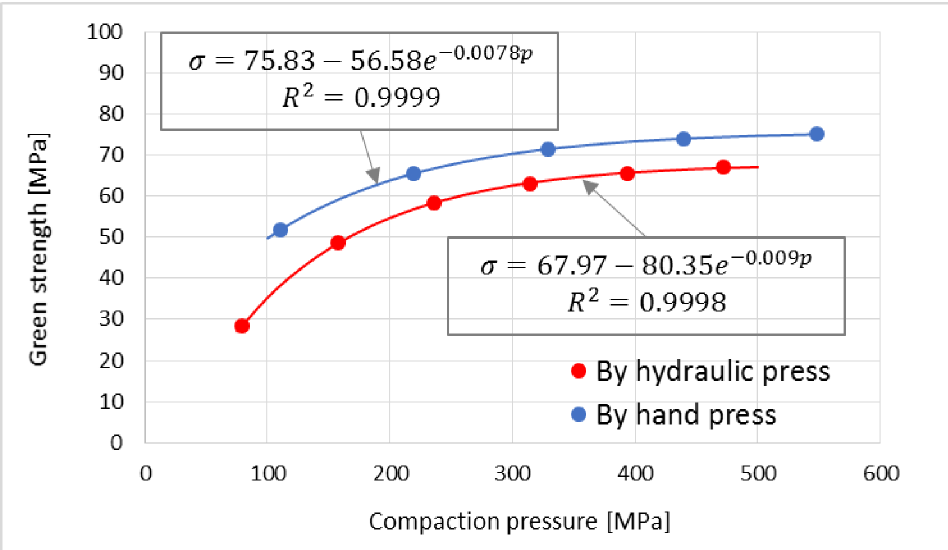

Fig. 6 Dependence of green strength of Bi100 samples on compaction pressure when compacting by different way on hydraulic and hand press

4. Discussion

The above-mentioned dependences are usable for optimization of the production process of the frangible bullet based on the bismuth powders. Using the dependence of the green density of the sample on the compaction pressure can determine the final shape of the bullet after compaction for achieving the required weight. Based on the relationship between the green strength and parameters of the pressing process (compaction pressure, pressing velocity and dwell time), the optimal conditions of producing and the process of producing frangible bullet can be determined, which meets the established tactical and technical requirements.

First shooting experiments with the pilot sample of the bullets have shown that the Bi100 material can be used to produce the cylindrical shot for the shotgun. However, Bi100 material has shown that it is not suitable for pistol projectile because of its low toughness and tensile strength. In the pistol projectile of Bi100 material, the mechanical damage occurs before shooting (e.g. transverse breakage during the elaboration cartridge or when inserting the cartridge into the gun chamber within a cycle of automatic load). For the production of pistol projectile, it is preferable to use the material in the form of a BiCu mixture of metal powders, where the above failure did not occur.

5. Conclusion

In the article, some possible experimental approaches for optimization of production process of bismuth frangible bullets are shown. The results of experiments enable to determine the optimal parameters of pressing process during manufacturing the bullet based on the bismuth powders:

- the compaction pressure when producing the bullet in the range of 300-400 MPa (for the Bi100 material), respectively 400-500 MPa (for the material BiCu),
- the pressing velocity of 50-70 mm min^{-1}. with the dwell time of 20-30 s.

The results can be used in the development of frangible projectile for shotgun and for pistol, which allows to shorten the stage of development of the bismuth frangible projectile not only for piece production, but also for mass production. However, these results cannot be generalized and the data in this article is only applicable as a methodological approach for manufacturing optimization when developing frangible projectiles from other materials.

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