ADVANCED TECHNOLOGIES AND MATERIALS VOL. 48, NO.1 (2023), 9 - 12
DOI: 10.24867/ATM-2023-1-002

Received: 07 April 2022
Revised: 20 April 2022
Accepted: 05 May 2022

Advanced Technologies & Materials

http://journal-atm.org
ISSN: 2620-0325 (print), ISSN: 2620-147X (online)

Original article

Explosive Forming: Analytical Methods for Determining the Mass of Explosives

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ABSTRACT

Explosive forming is one of the non-conventional impulse technologies of metal forming technologies and it is a relatively young technology that has not been fully explored. The origin, development and application of explosive forming technology is given in this paper, and the advantages and disadvantages are also described. Given the specificity of this technology, this paper presents the calculation of the mass of the explosive as the most important factor in this process and the calculation of the pressure of the shock wave. In fact, with conventional deep drawing technologies, it is possible to design the technology and follow the same steps to reach products of different dimensions. In explosive forming, this is a problem, and it is not possible to follow these rules. Experiments of explosive forming can only be performed by employees trained to work with explosives, following prescribed procedures.

Key words: *explosive forming; mass of explosive; velocity speed; pressure*

1. INTRODUCTION

Explosives can be considered chemical compounds or mixtures that, under the action of a certain mechanical or thermal impulse, cause a very fast chemical reaction, which is called an explosion. The explosion is accompanied by the release of a large amount of heat and the formation of heated gases under a pressure much higher than the ambient pressure. Due to the pressure difference, the gases expand very quickly, and a part of the energy is converted into work, which results in collapse and destruction. All explosives are defined by detonation speed, explosiveness, explosive energy, specific pressure, explosive density, sensitivity, and resistance to water and other external factors. Chemical decomposition occurs with explosives: burning, deflagration, and detonation. Deflagration is accelerated combustion with a flame where the explosive mixture in front of it is ignited. Detonation occurs when a shock wave of pressure passes through a mass of explosive material from the point of initiation. The difference between detonation and deflagration is that in deflagration the gaseous products move in the opposite direction of the flame front, while in detonation the gaseous products move in the same direction as the detonation wave. The speed of the detonation wave can be of the order of 10^3 m/s, and the speed of the spread of the flame front of the deflagration is of the order of 10^{-4} - 10^1 m/s [1].

Conventional metal forming technologies (forging, bending, deep drawing, extrusion, and other technologies) reached their maximum at one point in their development and there was no "space" left for further progress and development of these technologies. Given that there was a need for new products with larger dimensions, and wall thickness, and complex geometries, conventional

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Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

technologies could not give a good answer to this, even by combining several technologies. Although this combination of technologies in some cases could result in products that would approximately meet the mechanical properties or geometry, the use of multiple technologies required the need for more tools, presses, and manpower, so it was unacceptable from the economic point of view. At that moment, there was a need for new forming technologies or unconventional processing technologies by deformation. Non-conventional technologies include superplastic forming, hydroforming, incremental forming, microforming, electromagnetic forming, ultrasonic forming, explosive forming, and others. The paper focuses on explosive forming.

2. EXPLOSIVE FORMING

According to the deformation speed, metal forming technologies can be divided into three groups: quasi-static deformation where deformation speeds are from 10^{-2} to 10^{2} s^{-1}, superplastic forming 10^{-5} to 10^{-3} s^{-1}, and high-speed forming 10^{3} s^{-1}. Classic deformation processing procedures such as sheet metal forming and volume forming belong to the quasi-static area, i.e., the area of medium deformation speed. High-speed metal forming technologies shape workpieces at room temperature through the application of a large amount of energy in a very short time interval, usually milliseconds or microseconds. When a workpiece is shaped by high-speed technologies, the kinetic energy is converted into plastic deformation that is limited by the mold or die. Major research on these technologies was done in the late 1950s and early 1970s, although some of the technologies were discovered in the late 1880s.

Certainly, one of the best known, most widespread, and most used technologies is explosive forming. The difference between this high-velocity technology and conventional technologies is that this technology uses explosives as a source of energy. Explosives as such can be in solid, liquid, and gaseous state. The most famous explosive in solid form is trinitrotoluene (TNT), in liquid form nitroglycerin and in gaseous form methane-air mixture. The explosive used in deformation processing is called "high explosive" and very small amounts of explosives are used in deformation processing, in contrast to the use in mining or for military purposes. Explosive forming is used for deep drawing, compacting, cutting, welding, and expanding pipes [2]. The basic principle of this processing is to place the explosive at a certain distance from the workpiece. After the detonation of the explosive, the energy of the shock wave shapes the sheet or blank according to the shape of the die. In explosive forming, the medium can be in all three aggregate states: gaseous (air), liquid (water, oil) or solid (sand, rubber, salt) [3]. Explosive forming technology is successfully applied to form steel sheets with a wall thickness of up to 25 mm and a radius of up to 4 m. The mechanical characteristics of the formed piece are similar to those obtained by other technologies. One of the advantages of technology is adaptability. Namely, the die can be made of cheaper or easier to shape metal (iron, steel, aluminum, concrete, and wood) but also of hardened steel if high pressures are developed or a large number of workpieces need to be processed.

Explosive forming is successfully used with other technologies such as deep drawing, cutting, welding, expanding, it also can be used in the relaxation of residual stresses, in the compaction of powders, etc. At one point in past, the US government financed over 80 projects for the development of explosive forming at the same time [4].

One of the disadvantages of this technology is that there is no step traceability or predefined steps in the technology that lead to the finished product. This is especially pronounced when calculating the mass of explosives, which will be discussed in the next chapter.

3. CALCULATION OF EXPLOSIVE MASS

As emphasized in the previous chapter, one of the biggest problems in explosive processing is the calculation of the mass of the explosive. Namely, there are certain expressions for calculating the mass of explosives, but they refer to precisely defined conditions of the experiment. It cannot be asserted with certainty that the same expressions would be applicable in some other experiments with different parameters (type of explosive, type of medium, material). Vitezit V20 is a plastic explosive, and the rest of the calculation will be guided by it. Plastic explosives are the strongest commercial explosives of high density and explosiveness. The density of the cartridge is 1.5 kg/l, the explosion energy is 4157 kJ/kg, the detonation speed is about 6000 m/s, and the explosion temperature is 2639 ºC. For the purposes of the research, it is necessary to calculate the mass of explosives needed to shape a ball-shaped object composed of a trapezoid, as shown in Fig.1. The material of the workpiece is St12 and the calculation is made for thicknesses of 1 mm, 1.5 mm, and 2 mm.

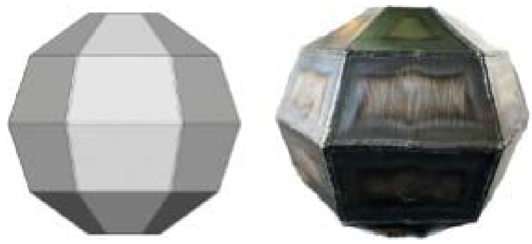

Fig.1 *3D model of the sphere and the blank*

The calculation was made according to three expressions, and the calculation of the shock wave pressure was also made.

The mass of the explosive charge, according to the literature [5], depends on the size of the stretch of the workpiece and its mechanical properties:

$$G = \frac{\Pi D^2\ \delta B}{e^{(1-\cos\varphi)(1+\alpha)}} \left\{ 2ln \left[1.5 - \frac{1}{2\left(1 + \frac{4f^2}{D^2}\right)} \right] \right\}^{(\alpha+1)} \qquad (1)$$

Where D - the diameter of the die opening (mm), s - the thickness of the sheet (mm), B and α - the coefficient of approximation of the diagram of real stresses, which are: α = 0.24 for Al alloys and B = 327 (MPa); α = 0.16 for martensitic steels and B = 1900 (MPa), f - die depth (mm), φ - angle between matrix and explosive charge. The distance R between the explosive charge and the workpiece with a diameter D of the picture is taken within the limits: R = (0.2 ÷ 0.4) D for steels and alloys with high mechanical properties, R = (0.3 ÷ 0.5) D for steels with low mechanical properties, r_0 – radius of the explosive charge depends on the size of the mass of the charge G that is determined. The height of the water column H above the explosive charge can be taken within the limits of H = (20 ÷ 25) r_0.

The mass of the explosive charge obtained by some expressions can differ by up to 200%. The above-mentioned points to the importance of researching the optimal amount of explosives that would provide enough energy to deform the sheet while causing minimal load on tools and containers.

The authors [6] talk about Eq. (2) and Eq. (3) by which the necessary mass of explosives per unit of wetted surface can be reached with a relatively small deviation for copper and steel.

$$G = 2.69 \cdot 10^{-5}\, \sigma_m \,(\delta^{0.233} K R^{0.14})^{4.134} \qquad (2)$$

It can be seen from Eq. (2) that the required mass of explosives per unit area can be expressed through the tensile strength σ_m and based on which satisfactory results are obtained.

$$G = 0.0113\delta^{0.972} K^{4.134} R^{0.582} \qquad (3)$$

Where δ - the thickness of the sheet that is pulled out in mm, K - drawing ratio, R - the distance between the explosive charge and the workpiece in mm.

According to (1), (2) and (3), the mass of the explosive charge for a material thickness of 1 mm would be 10.14 g, 18.67 g and 23.42 g.

$$G = \frac{\Pi D^2\, \delta B}{e^{(1-\cos\varphi)(1+\alpha)}} \left\{ 2ln \left[1.5 - \frac{1}{2\left(1+\frac{4f^2}{D^2}\right)} \right] \right\}^{(\alpha+1)} = \frac{\pi \cdot 0.210^2 \cdot 0.001 \cdot 1900}{e^{(1-cos 180)(1+0.16)}} \left\{ 2ln \left[1.5 - \frac{1}{2\left(1+\frac{4\cdot 0.105^2}{0.210^2}\right)} \right] \right\}^{1.16} \qquad (4)$$

$\boldsymbol{G = 0.00101468\ kg = 10,14\ g}$

$$G = 2.69 \cdot 10^{-5} \cdot \sigma_m \cdot \left(\delta^{0.233} \cdot K \cdot R^{0.14}\right)^{4.134} = 2.69 \cdot 10^{-5} \cdot 340 \cdot (1^{0.233} \cdot 1 \cdot 105.24^{0.14})^{4.134} = 0.1354\ \frac{kg}{m^2} \qquad (5)$$

$\boldsymbol{G = 0.01867\ kg = 18.67\ g}$

$$G = 0.0113\delta^{0.972} \cdot K^{4.134} \cdot R^{0.582} = 0.0113 \cdot 1^{0.972} \cdot 1^{4.134} \cdot 105.24^{0.582} = 0.1698\ \frac{kg}{m^2} \qquad (6)$$

$\boldsymbol{G = 0.02342\ kg = 23.42\ g}$

It is important to note that in Eq. (1) the diameter of the workpiece, the distance of the workpiece from the die and the thickness of the material must be expressed in meters, and the result is obtained in kilograms, which must be converted into grams.

When calculating the mass for a sheet thickness of 1.5 mm, the following results are obtained according to (1), (2) and (3).

$$G = \frac{\Pi D^2\, \delta B}{e^{(1-\cos\varphi)(1+\alpha)}} \left\{ 2ln \left[1.5 - \frac{1}{2\left(1+\frac{4f^2}{D^2}\right)} \right] \right\}^{(\alpha+1)} \qquad (7)$$

$\boldsymbol{G = 0.01522025\ kg = 15.22\ g}$

$$G = 2.69 \cdot 10^{-5} \cdot \sigma_m\, (\delta^{0.233} \cdot K \cdot R^{0.14})^{4.134} = 2.69 \cdot 10^{-5} \cdot 340 \cdot (1.5^{0.233} \cdot 1 \cdot 105.24^{0.14})^{4.134} = 0.2\ \frac{kg}{m^2} \qquad (8)$$

$\boldsymbol{G = 0.02758\ kg = 27.58\ g}$

$$G = 0.0113\delta^{0.972} \cdot K^{4.134} \cdot R^{0.582} = 0.2518\ \frac{kg}{m^2} \qquad (9)$$

$\boldsymbol{G = 0.03473\ kg = 34.73\ g}$

Calculation of the mass of the explosive charge for a workpiece with a wall thickness of 2 mm gives the following results:

$$G = \frac{\Pi D^2\, \delta B}{e^{(1-\cos\varphi)(1+\alpha)}} \left\{ 2ln \left[1.5 - \frac{1}{2\left(1+\frac{4f^2}{D^2}\right)} \right] \right\}^{(\alpha+1)} \qquad (10)$$

$\boldsymbol{G = 0.02029\ kg = 20.29\ g}$

$$G = 2.69 \cdot 10^{-5} \cdot \sigma_m \cdot (\delta^{0.233} \cdot K \cdot R^{0.14})^{4.134} = 2.69 \cdot 10^{-5} \cdot 340 \cdot (2^{0.233} \cdot 1 \cdot 105.24^{0.14})^{4.134} = 0.26396\ \frac{kg}{m^2} \qquad (11)$$

$\boldsymbol{G = 0.03640\ kg = 36.4}\ g$

$$G = 0.0113 \cdot \delta^{0.972} \cdot K^{4.134} \cdot R^{0.582} = 0.0113 \cdot 2^{0.972} \cdot 1^{4.134} \cdot 105.24^{0.582} = 0.3331109\ \frac{kg}{m^2} \qquad (12)$$

$\boldsymbol{G = 0.04594\ kg = 45.94\ g}$

The obtained results can be presented in the following table, Table 1.

Table 1 – Required quantities of explosives for certain material thicknesses

	Thickness 1 mm	***Thickness 1.5 mm***	***Thickness 2 mm***
Eq. 1.	10.14 g	15.22 g	20.29 g
Eq. 2.	18.14 g	27.58 g	36.4 g
Eq. 3.	23.42 g	34.73 g	45.94 g

According to the above calculation, it is possible to present the same results graphically (Fig.2).

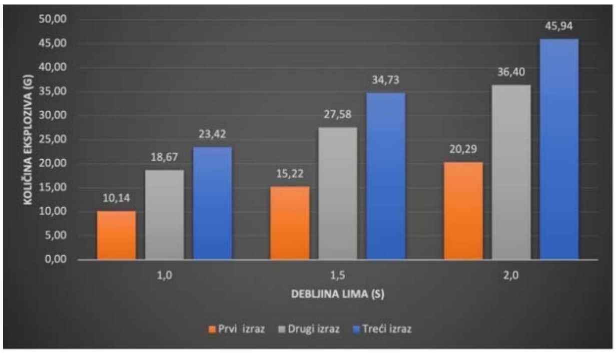

Fig. 2 *Graphic representation of the amount of explosives*

The shock wave pressure was calculated according to Eq. (13), where the calculation was made exclusively for the highest calculated mass of the explosive charge per material thickness:

$$p_v = 287.2739 \cdot lnG + 322.6927 \cdot lnV_E - 682.0897 \cdot lnR - 1866.4059 \quad (13)$$

$$p_v = 287.2739 \cdot ln0.023 + 322.6927 \cdot ln5000 - 682.0897 \cdot ln0.105 - 1866.4059 \quad (14)$$

$$\boldsymbol{p_v = 1335.64\ bar}$$

$$p_v = 287.2739 \cdot ln0.034 + 322.6927 \cdot ln5000 - 682.0897 \cdot ln0.105 - 1866.4059 \quad (15)$$

$$\boldsymbol{p_v = 1447.93\ bar}$$

$$p_v = 287.2739 \cdot ln0.046 + 322.6927 \cdot ln5000 - 682.0897 \cdot ln0.105 - 1866.4059 \quad (16)$$

$$\boldsymbol{p_v = 1534.77\ bar}$$

The results are also shown graphically in Fig.3.

3. CONCLUSION

The paper presents a comparison of the analytical results of the required mass of explosives for obtaining spheres of different sheet thicknesses. As already mentioned, the calculation of the mass of explosives is an insufficiently researched parameter when planning an experiment in blast processing, and the results for the same conditions can drop by over 200%. In this case, for the same sheet thickness using different expressions, the calculation showed a deviation of 130%. It is recommended that when making an experiment, a lower value of explosives is always taken, which, if necessary, is gradually increased until the desired results are obtained. An excessive amount of explosives can negatively affect the experiment and destroy the workpiece or tool. Explosive forming is an unconventional metal forming technology that is still under development, but in the future, it will certainly be increasingly used in the production of work items of different materials.

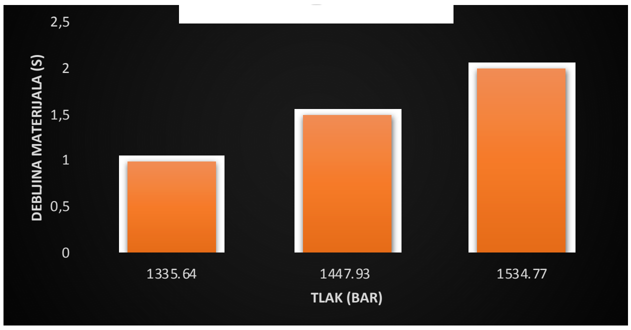

Fig. 3 *Calculation of shock wave pressure*

ACKNOWLEDGEMENTS

This paper was created as a part of the research of the scientific research project *"Influence of detonation speed on the mechanical properties of materials during freeform explosion"* number 05-35-2042-1/22 funded by the Federal Ministry of Education and Science.

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