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# EXPLOSIVE FORMING OF AEROSPACE COMPONENTS

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**Abstract** Results are presented of the development of explosive forming technology for metal sheets and plates. Explosive forming is labor intensive, but requires only single-sided tooling it can be used economically for small series of hard to deform metals, like nickel, titanium and aluminum alloys, that are generally used in aerospace applications. As the alloys can be formed in their hardened (tempered) condition, the formed components do not need a heat-treatment afterwards (at which deformations generally occur). Plate velocity calculations and measurements can be used for engineering calculations. Examples are given of aerospace parts of aluminum and nickel alloys for process development and the fabrication of demonstrators.

**Keywords:** Dynamic plastic deformation, Explosive forming, Gurney-theory.
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## INTRODUCTION

Explosive forming is a high-energy-rate plastic deformation process for metal plates and tubes in which an explosive charge is used as energy source. It has been developed about fifty years ago and has been used in the seventies of the last century for several aerospace components such as the forming of large aluminum alloy sheets into dome segments for the Saturn rockets in the USA [1]. Nowadays, the process is only applied by a small number of companies and research institutes. An overview of this technology and its users has recently been published [2].

Only single sided dies are required which is a large benefit considering the high machining costs for the manufacture of dies with complicated shapes. Also no large machines or special power supply are required, which enable the forming of large and thick-walled metal plates. However, the clamping of metal plates and the handling of explosive charges make it a rather labor intensive activity which drives up the recurring costs. The combination of its modest start-up costs and the labor intensive character make this forming process only profitable for the fabrication of single pieces and small series.

## THE FORMING PROCESS

Explosives form a powerful, cheap and highly reproducible source of energy. Contrary to other forming methods it does not require a machine. This is considered as an advantage since the finite size and strength of a machine intrinsically limit the products in size and thickness that can be formed. As opposed to that, an explosive charge can be adjusted to any scale strength and thickness of the metal to be formed.

The explosive charge can be concentrated in one spot or distributed such that the energy release is spread over the metal evenly (using detonation cords). Usually, the explosive is not in direct contact with the plate, but situated under water which is a good shock wave transmitting medium since it is a rather incompressible and pore free space filler.

The plate is placed over a die and clamped at the edges. The space between the plate and the die may be vacumized before the forming

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process in order to prevent back pressure (and local metal oxidation due to high gas temperatures) from compressed air.

Usually the die and explosive charge are lowered in a water tank in which the forming process takes place. However, for small parts it is easier to place a water filled bag on top of the die and detonate the explosive charge placed in the water at the required stand-off.

At the moment of detonation a shock wave is generated in the water which propagates in all directions with a speed depending on the shock intensity (typically about 1600 meter per second a few centimeters away from the high explosive charge). When the shock wave arrives at the metal surface it is reflected back into the water and the metal obtains momentum and starts to move into the die cavity. The velocity of the metal depends on the intensity of the shock wave in the water and the mass of the plate, but is generally on the order of tens of meter per second. Due to the much higher velocity of the shock wave, the metal starts to move practically as one body. As the water can only generate stress perpendicular to the metal surface, the metal is also accelerated only in this direction. Due to the constraints generated by the die and the clamping of the metal, the periphery of the metal can not move together with the rest of the plate and the plate will start to bend over the radius of the edges of the die. This bending motion is then moving through the metal plate with its own velocity.

Depending on the amount of clamping the plate will experience an in-plane tensile stress and the metal will stretch (resulting in plate thinning) or the plate will start to pull in metal from below the clamps. Normally both plate reactions occur at the same time. The metal will be slowed down as more and more of its kinetic energy is transferred to plastic deformation of the plate.

When all kinetic energy is used before the metal has touched the die surface, the metal is free-formed and will need additional (explosive) forming steps.

When the shock wave accelerated metal hits the die surface it will be formed according to the shape of the die and the required form is obtained.

## GURNEY THEORY

A simple and first order estimate of the *maximal* plate velocity can be obtained using the Gurney theory [3]. This theory (based on energy balance) is capable of calculating the maximal velocity of explosively accelerated metal plates, spheres and tubes. Apart from the empirically determined specific energy of the explosive used (the so-called Gurney energy of an explosive type, $E_g$), only the mass ratio between the explosive (C) and the metal part ($M_P$) is needed. The original theory derifed in [3] applies to a cylinder completely filled with explosive material. Due to the presence of the water the theory has to be slightly adjusted, resulting in equation 1. The plate velocity then also depends on the mass of the water and on the inner (a) and outer (b) radius of the water (see figure 1). Depending on the standoff distance and the form in which the explosive has been applied underwater (concentrated or as a linear charge), the shocked water will have the form (and volume) of a sphere or cylinder. For example, we will calculate the maximal velocity of an expanding aluminum cylinder with a radius ($b_0$) of 90 mm, a wall thickness of 2.5 mm and a height of 250 mm. The cylinder is filled with water and a detonation cord is positioned on its axis of symmetry (12 g/m PETN, radius $a_0$ of 4 mm). First, the Gurney velocity of PETN should be found; from literature one finds $\sqrt{2E_{g,PETN}}$ equals 2930 m/s [3]. Then the mass of the plate and the shocked water should be calculated. However, for thin plates and regular stand-off distances (>50 mm), the mass of the shocked water greatly exceeds the plate mass and an upper bound of the plate velocity can be found using only the shocked water mass. In our case the metal cylinder is free formed (die less) and completely surrounds the explosive charge. Therefore, the efficiency of the forming process will be rather high. The detonating cord generates a cylindrical shock front in the water, with a velocity distribution that relates to 1/r. The highest water velocity occurs at the explosion products-water interface. The water in the cylinder has a volume of 6.4 liter and therefore weights 6.4 kg. The mass of the aluminum cylinder $M_P$ is about 1 kg. The mass of the explosive charge is only 3 gram (0.25 m * 12 g/m).

$$V_p = \sqrt{2E_g}\left(\frac{M_P}{C} + \frac{M_W}{C}\frac{2b^2}{b^2 - a^2}\ln\left(\frac{b}{a}\right)\right)^{-1/2} \quad (1)$$

Using equation (1), initially a maximal plate velocity of 34 m/s is obtained. Upon expansion of the cylinder the kinetic energy distribution within the water further accelerates the plate. At a radial expension of 10 mm the plate velocity is 43 m/s.

The initial velocity of the plate is close to the 30 m/s that has been measured experimentally using strain gauges on explosively expanded cylinders, and laser-triangular plate position measuring methods.

The laser positioners are based on the measurement of the position of the laser light reflection on the (moving) plate surface.

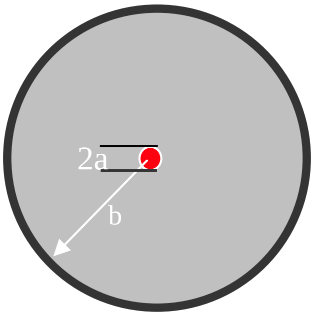


**FIGURE 1.** Schematic set-up for explosive forming a water filled metal cylinder (mass M) with a detonation cord (mass E) at a stand-off (R).

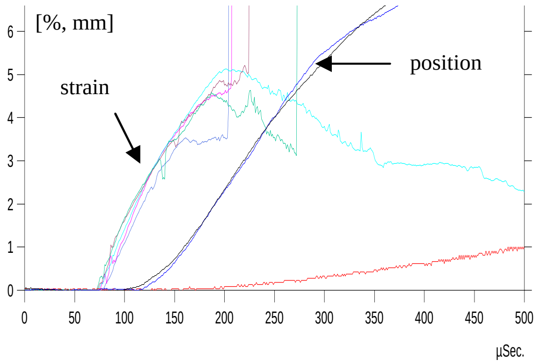


**FIGURE 2.** Result of strain and plate position measurements using strain gauges and laser reflection.

In Figure 2 the results of the measurements are presented. All three strain gauges give the same strain and strain-rate information, and two laser triangular positioners also agree. The third positioner had a wrong setting (integrating) resulting in a too low measuring response. From the slope of the lines (strain and position versus time) one can determine the strain-rate (375 $s^{-1}$) and plate velocity (30 m/s). The calculated plate velocity is not far off but indeed an upper bound velocity. The measurements do not show a further acceleration of the metal plate upon cylinder expansion. This is probably due to energy escaping the water cylinder system. This is not surprising considering the small length to diameter ratio of the cylinder used here.

Once the (upper bound) maximal plate velocity is known, one can estimate the strain-rate and the kinetic energy of the plate. Knowing the strain required for the metal preform to obtain the required (die) form and the yield stress of the metal, the required energy for the forming can be compared to the available kinetic energy of the metal. In many cases the final form can only be obtained by explosively forming the product in at least two forming steps, e.g. a forming and a calibration shot.

## EXAMPLES

Research has been done on explosive forming segments of an AA2024 stiffening ring for the main engine frame of ESA's space vehicle Ariane 5. The standard fabrication route involves hammering using several (lead) dies where the alloy is in the annealed condition. This has to be followed by a heat treatment to the high strength aged condition (T3).

By explosive forming this alloy can be formed directly in the T3 condition and only a single sided die is needed. An explosively formed ring segment together with the starting metal plate is shown in Figure 3.

A second example of the explosive forming of aerospace components is the forming of a gas mixer for gas turbine engines. This product is typically made by welding together numerous hot formed segments (each containing one fold). The double curved product can, however, be made out of just one flat plate by explosive forming, see Figure 4. The starting material is a circular disk which is first simply bended to contain the number of folds that are required, see

Figure 4(a). This preformed plate is then positioned in a die that has the double curved form. By explosive forming using an axially positioned under water explosive charge, the final shape is obtained, see Figure 4(b). This fabrication method is quite simple and a lot of weld lines (as well as their inspection) are avoided.

## CONCLUSIONS

Explosive forming is a batch process for small series of complex parts of hard to form materials. The forming in more then one process step makes it rather labor and costs intensive, thereby reducing the production capacity. However, only single-sided dies are used, which will reduce the initial production costs.

This forming method is capable of fabrication of complicated double curved products with the metal in the aged (hardened) condition. This avoids heat treatments and welding of several small parts after their forming and therefore may lead to better and less expensive fabrication of products.

For engineering calculations of the forming process, the plate velocity can be estimated using the Gurney-theory. Here one has to incorporate the mass of water as well as its velocity distribution.

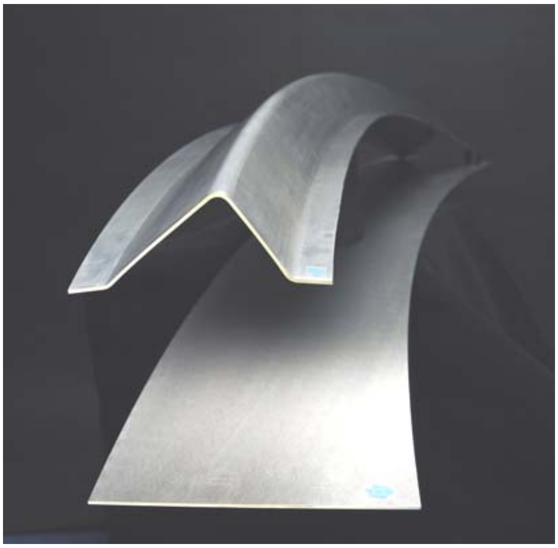

**FIGURE 3.** Starting material (AA2024-T3) and explosively formed ring segment.

(a)

(b)

**FIGURE 4.** Gas mixer for gas turbine exhaust made by explosive forming (b) using a preformed disk (a). (Courtesy of Exploform BV)

This has been supported by strain and plate velocity measurements that were obtained using (resistance) strain gauges and laser-triangular positioners, respectively.

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