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HIGH-ENERGY RATE FORMING OF METALS

by

H.P. Tardif

DEFENCE RESEARCH BOARD

CANADIAN ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

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H.P. TARDIF

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NOTE

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ABSTRACT

A general review of a new metal forming technique commonly called explosive forming has been carried out in this paper. The main variables involved are briefly described. The materials and shapes formed to date and the metallurgical and dimensional aspects are discussed. The theories as to why explosive forming works are mentioned. Other metal working operations performed by means of explosive energy such as hardening, welding, the pressing of powders, etc. are reported. Finally, the use of explosive forming in the missile industry and the broad aspects of Canadian work in explosive metallurgy are reviewed.

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HIGH-ENERGY RATE FORMING
OF METALS

A novel way of metal forming called "high-energy-rate forming" or, more commonly, explosive forming, has already made headlines in many technical magazines and newspapers.

Still in its infancy, this revolutionary method has made great strides during the last few years. It consists, as the name implies, in applying energy to the work piece at considerable input rates, this being achieved generally by the use of high-energy materials such as explosives and propellants or by means of gas actuated presses.

HOW IT IS DONE

Although many gas actuated presses are being developed, a typical example is the "Dynapak" designed by "Convair". It consists of a compressed gas actuator which releases high-level energy with precision control of the acceleration - time relationship. The piston attains an acceleration of 1,000 G's and a velocity of 5,000 fps. to a precision of ±½ fps. The reaction system of the machine is based on the concept of dynamic restraint rather than static load carrying capacity. In one model, two cylinders simultaneously force steel heads towards each other at impact energies of 1,000,000 in-lb. A die and a blank are mounted on one end while a rubber pad is mounted on the other for forming operations. For extruding or forging, similar arrangements are used.

A second method of high-energy-rate forming consists in using propellant gases as a source of power. The gas is generated by a blank type cartridge and can be applied directly to the work piece or through an hydraulic medium or on a piston-hydraulic media-work piece arrangement. Propellants do not detonate but burn rapidly, and the work on the blank is performed by the pressure of the expanding gases. Consequently, a closed die is necessary for this type of forming.

In the third method of forming, the energy source is a high explosive. These materials detonate instantaneously, producing an intense shock wave which probably does the forming. The process is carried out in an open die contoured to the shape desired. This die is generally the female die. In explosive forming, the male die is replaced by the explosive shock wave which acts as a flexible die or punch, giving an optimum application of stress uniformly applied on the whole piece at all stages of the process. This "flexible" or "variable size" punch permits the formation of complex shapes impossible to obtain with solid die and presses.

Hybrid processes include high-velocity presses actuated by propellant instead of ordinary gases. Drop hammers with trapped rubber heads are also accelerated by explosive methods.

The various arrangements by which the explosive energy is transferred to the work piece are numerous and depend on the shape and size of the end-item and on the operation to be carried out, i.e. drawing, bulging, etc. Figure 1 shows some of these arrangements. They consist generally of an explosive or propellant charge, a blank which can be a sheet, a tube or a cone of metal, a constraining die, and an energy transmitting medium. The main variables involved in the setup are as follows:

a) amount and type of charge,

b) stand-off distance,

c) energy transfer medium and confinement,

d) Evacuation of die cavity,

e) Shaping of shock wave front.

Other considerations include the type, strength and thickness of metal to be formed, the pressure required, duration and rate of application, metallurgical changes produced, and die design and construction.

CHARGE

Many firms are at present establishing complete lines of metal forming cartridges of specified characteristics, such as pressure-time, pressure-cavity volume, pressure-cavity shape and pressure-powder charge weight curves. With these data available it will be possible to choose the proper cartridge for the job.

In the case of high explosives the amount of charge is again a function of confinement, stand-off, energy transfer media and of the type of explosive. The trend seems to be towards the use of high explosives which have very sharp and abrupt pulse or pressure time curve, i.e. an energy release taking place in a very short time, or, in other words, a high-detonation velocity. For a given explosive, this detonation velocity is function of its density.

The charge can be in the form of a liquid, a powder or solid shapes such as cylinders, sheets, pellets, rods or cord and can be tailored for specific applications. The shape of the charge will affect the shock wave pattern, as will be seen later, and this will have a great effect on the forming process. Primers and booster charges will also influence the energy, impulse and pressure obtained.

Some of the high explosives used are PETN, RDX, TNT, nitroglycerine, 30% ammonia gel and cyclonite. The pressures developed are very high, varying from about 490,000 psi for 30% ammonia gel to 1,200,000 for nitroglycerine. They are chosen on the basis of the pressure developed, thermal mechanical or shock sensitivity, ease of initiation, power and heat of explosion.

STAND-OFF DISTANCE

As the distance between charge and blank increases, the peak pressure decreases and the duration of the shock increases. The distance can be varied in fairly wide limits but the optimum distance should be that which will produce the forming desired with the smallest charge of explosive and without damage to the blank.

The pressure obtained at a given distance varies with the shape of the charge. It is inversely proportional to the distance for sheet explosives, to the square of the distance for cords or cylindrical charges and to the cube for pellet of explosives.

ENERGY TRANSFER MEDIUM AND CONFINEMENT

Experiments have shown that liquids and soft or powdery mediums such as wax or talc powder are efficient mediums for transmitting the shock or pressure wave to the blank. In most cases water is used instead of air and, consequently, the forming is carried out under water as shown in Figure 1c. For experimental purposes it is not necessary to have a permanent installation such as a deep pit. A cardboard container filled with water and placed on top of the die and blank will fulfill the same purpose.

Such mediums have the further advantage besides transmitting energy, of dampening the shock and preventing a slight pitting at the surface of the blank, which can be caused by particles from the detonator or by defects at the surface of the charge. The pressure can also be increased by confining the explosion by means of closed or semiclosed dies and of confinement tubes.

EVACUATION OF DIE CAVITY

In many cases, it may be sufficient to drill a vent-hole at the bottom of the die to let the air escape from the die cavity. But, when the depth of draw is large and the tolerances critical, the die cavity should be evacuated. In this case, the vent-hole is plugged with a porous material ground flush with the die internal surface to prevent markings on the finished piece. The die cavity is then evacuated through the porous plug.

SHAPING OF SHOCK WAVE FRONT

It is now possible to produce stress wave fronts in shapes best suited to the configuration of the item to be formed. This can be accomplished by using charges of various shapes, by initiating the charge at many points, and by using standard wave shaping methods which incorporate inserts of inert materials and assemblies of explosives of different detonating velocities. These methods permit accurate control of the shape of the shock front so that spherical, linear plane and even concave pressure wave fronts of different radii of curvature can be obtained. In one case, for example, a spherical charge is used and initiated at the center so that explosion will progress uniformly from the center outward to produce a spherical wave.

Parabolic reflectors above the charge will also reflect and concentrate the pressure wave at desired points on the blank.

Instead of one large solid charge, smaller pellets can be distributed at various points when a large or complicated shape is to be formed. In this case, each pellet or cluster of pellets must be detonated simultaneously.

By changing any of the above variables, the shape of the pressure-time curve will be affected and the most suitable conditions can be found to shape a particular configuration. This may involve countless hours of trial and error. However, charts should be available soon that will show the optimum combination for a particular set of conditions of metal shape, type, thickness, etc.

DIE DESIGN AND CONSTRUCTION

As mentionned previously, only female dies are necessary, and a shape which requires many operations in a press can be formed directly in one die.

Die materials are chosen on the basis of tolerances, shape and number of formed pieces required. When limited quantities are required, it appears that relatively inexpensive dies can often be used. A wide variety of materials have been tested for die construction including tool steel, mild steel, kirksite, concrete, wood, epoxy plastics reinforced with glass cloth and fibers, plaster, paper, clay, aluminum, lead-zinc alloys, etc. Plaster will only last one shot, concrete several and reinforced plastics almost indefinitely. In certain cases though alloys have been shaped over dies of much softer materials.

A typical forming die for U.S. Navy tank sections is made as follows: Two mild steel shells one inch thick form a cylinder 3 ft. in diameter by 4 ft. high. Inside the cylinder is a cast liner made up of an epoxy resin-pea gravel mixture shaped to the required contour. A fiberglass coating 1/8 in. thick is applied over the die contour and pealed with an epoxy surface coat to prevent water absorption. Dies such as these are claimed to last indefinitely if properly used.

The tendency in certain cases is to partly or completely close the die even with high explosives so that large and heavy dies have to be used. In this manner, the noise is dampened and very little water is spilled so that explosive forming can practically be carried out indoors.

SHAPES PRODUCED AND OPERATIONS PERFORMED

When the explosively formed shapes are driven with sufficient force against the die, they show no spring back. This characteristic of explosive forming is used extensively to form shapes with accuracy, and to size mechanically preformed pieces. One of the first application appears to have been the explosive restrike of titanium jet engine inlet-guide vanes.

The vanes are preformed from flat blanks by folding and welding. The blanks are placed into split dies having the required airfoil configuration and a cartridge is inserted in a sliding block firing chamber adapted on the dies. After firing, the gas pressure bulges the titanium vane to the required shape given by the die. This is the only method found that would form titanium without spring back. Tolerances as close as ± 0.005 in. can be held.

The sizing of large rocket motor cases is also carried out by this method with improved axial concentricity. Figure 2 shows one of these rocket motor tubes in the sizing die.

The forming of the simpler shapes such as jet engine sound suppressor tubes, Figure 3, streamlined fuel tanks for the IM-99 Bomarc Missile, propellant tank domes or ends and rocket tubes, has already reached production, and similar applications are rapidly growing. Progress is encouraging on more intricate shapes such as cones and nozzles.

Explosives had been used previously for simple operations, such as dimpling, piercing, riveting, flaring, shearing and punching. Processes have now been developed for bulging, upsetting, expanding, cupping, deep-drawing, extruding, forging, inlaying, embossing and swaging operations.

Other interesting metal forming or shaping operations under consideration by explosives experts include casting, compacting of powder, welding, machining and hardening. In fact, hardening of metals by explosives has just been perfected to the point where it is a commercial operation used by many firms. Parts like railway frogs, tractor grouser plates and dipper teeth of cast austenitic manganese steels are now hardened by detonating a sheet of explosive placed in contact with the surface to be hardened. The hardness of such parts increases by 300 points Brinell, the tensile strength doubles and the yield quadruples. The shock wave transforms the soft austenite into strong and wear resistant martensite.

Casting, welding and machining are in the development stage. High-velocity flow of molten metal would permit the filling of thinner sections and complex shapes before freezing of the metal. Experiments on high-speed machining have been carried out at velocities of up to 162,000 sfpm on heat-treated 4340 steel of 45 to 52 Rockwell C hardness using explosively accelerated specimens. The hardness of the work piece has little effect on the cutting action. As the velocity goes up, the cut becomes smoother with less deformation. More practical machines are being developed to test-machine materials at super high velocities.

Welding of dissimilar metals, cladding pipes, tube linings, tubes in header sheets, are all operations performed on an experimental scale. In one laboratory, 1100-O aluminum 0.051 in. thick has been welded to itself and to Inconel.

Finally, the power of explosives is also applied to powder metallurgy methods and it is expected that pressing of powders will soon be carried out in this manner.

It is thus evident that not only sheet products can be formed but that, on the contrary, practically any metal working operation can be duplicated using explosive energy.

MATERIALS FORMED

In these processes, practically all types of constructional materials have been tried, such as carbon and alloy steels, stainless steels, aluminum, copper and their alloys, titanium alloys, hastelloy X, tricent vascojet 1000, multimet, molybdenum, magnesium, thorium nickel and cobalt base super alloys, both in their annealed and heat-treated states. Facilities now exist for forming pieces as large as 20 ft. in diameter. Thirty-two-foot-diameter dies are under construction.

The Dynapak produces parts that cannot be formed in any other conventional way, because the large pressures involved force the metal into every crevice of the die. It can extrude web thicknesses to one-hundredth of an inch and extrude non symmetrical shapes with high ratios of thick to thin sections, operations which are impossible to perform in conventional extrusion. It can also forge to zero draft angle. The surface finish is claimed to be very good.

Dynapak has produced extrusions of arc cast and sintered tungsten, of columbium, zirconium, titanium and nickel base powdered metal, some of them in 10 to 1 ratio and more.

In explosive forming some unusual behavior has been observed. The ductility of Type 347 stainless steel, normally 30 - 40 per cent in standard tensile test, was increased to 75 per cent in explosive loading. That of 1020 carbon steel was increased from 42 per cent normal elongation to 70 per cent during the forming of rocket nozzles.

METALLURGICAL AND DIMENSIONAL ASPECTS

The microstructural changes taking place in metals submitted to the detonation of contact explosive charges are complex and varied. At very high pressures near the explosive metal interface, evidence has been obtained that certain metals can even show phase transformation. For example, the alpha iron phase of mild steel would transform to gamma iron under high pressures and back to alpha iron after pressure release. The hardness can also reach values equivalent to those obtained after 95 per cent reduction of thickness by rolling, although practically no macroscopic change in dimensions is observed.

In the case of explosive forming the charge is not generally placed in contact with the work piece so that the changes are not so drastic. The metal is hardened first by the passage of the shock wave through it, and secondly by the plastic deformation due to the change in shape as the metal takes the shape of the die. Moreover, work-hardening of metals is affected by the rate of deformation. For these reasons, it is evident that there is no direct relationship between macroscopic changes in dimensions and changes in hardness (See Figure 10).

The metallurgical changes taking place are functions of the amount of deformation, and in processes involving severe plastic flow, such as forging and extrusion, these changes should be extensive both during and after the process. They would involve recrystallization and grain growth, formation of flow lines textures, preferred orientations, etc. In simple operations, such as stretching, bulging, embossing, etc., there is little change in grain size up to about 20 per cent change in thickness but the usual deformation markings, such as mechanical twins, slip lines, deformation bands, etc., will be present.

The metal will flow in the die and take the exact shape required, provided the proper conditions are used. Small defects in the die will be faithfully reproduced at the surface of the piece which will be good inasmuch the surfaces of the die and blank are good.

The tolerances in finished products can be held very close. Figure 4 shows the results obtained on the sound suppressor tube of Figure 3. The parts are extremely uniform and the scrap rate is low.

It would appear that in most cases no heat-treatment or machining operation is necessary except possibly for trimming or cutting, for example, when two parts are made in the same die. This would naturally depend on the strength requirements of the finished product. In certain cases, parts have been explosively formed from full hard Type 302 stainless steel. These parts would have the maximum strength they can ever get. In other cases it may be necessary to form in the annealed condition and heat-treat afterwards for maximum strength, although explosive forming can be carried out on steel heat-treated to quite reasonable strength levels.

It is claimed that residual stresses are considerably reduced so that stress relieving treatments are probably unnecessary in most cases.

WHEN TO USE HIGH-ENERGY-RATE FORMING

Explosive forming can be used with best advantage in the following cases:

a) for very large parts of size beyond the capacities of available presses.

b) for intricate parts difficult to make by conventional processes.

c) with metals showing an appreciable increase in ductility at high rates of strain, permitting a greater deformation of the metal.

d) for reducing spring back in order to achieve close tolerances.

The advantages are both technical and economical. When pieces too large to be taken by existing presses are to be formed, it is obvious that considerable reduction in die and equipment cost will be obtained. In general, it can be said that explosive forming is most economical when the complexity, quantity, size, and nature of materials make conventional press forming too expensive or unfeasible. It also gives better definition, good surface finish, and requires the least investment in tools and dies besides producing often in one step pieces normally fabricated in many operations.

In difficult problems, formability, rather than cost, should be the prime factor for choosing the process. But in many cases, manufacturers report huge savings. One firm claims that the cost of forming fan hubs by explosive forming is only 15 per cent of that of spinning the same piece. Another firm reports a case where a jet engine piece required 8 hours to form on a drop hammer because of repeated hammering and interim annealing treatment. This piece can be formed in 15 minutes by explosive forming.

High-velocity impact machines such as Dynapak also represent low initial investment. This machine built by Convair is available to industry in three sizes. The equipment is easy to operate, is controlled by only 3 simple dials and does not require any highly skilled operators. The company sends an engineer to customers plant for a period of 5 days to instruct and train their personnel in the uses and applications of this machine. The cost of Dynapak is approximately 75 per cent less than that of conventional forging equipment. The machine does not need any extra equipment, such as steam generating plants, heavy flooring structure, etc., as is required for conventional forging steam hammers. Moreover, Dynapak is more versatile and can forge to better tolerances and limits than conventional forging presses.

Although explosive forming will not replace repetitive press forging for large volume production of easily formed shapes, it will find its uses for applications beyond presses capabilities and is intended to supplement conventional methods. As a general rule of thumb, it is claimed that a sheet metal part formed conventionally with tooling acquired at a cost of $100,000.00 can be formed by explosive forming with tooling costing less than $10,000.00. This small capital investment is a very attractive proposition.

In general, propellants can be stored and used in plants while high explosives are prohibited. Propellants are in fact used indoors for forming in closed systems while high explosives are used outdoors in open or semi-open systems. Outdoors high-explosive forming may be preferable for very large pieces. One firm is now making dies suitable for forming pieces 32 ft. in diameter.

Explosive forming permits the use of heat-treated stock. The problems of warpage, expansion or shrinkage which normally follow heat-treatment are thus removed.

WHY EXPLOSIVE FORMING WORKS

The reasons why an increase in ductility is obtained with certain materials, that cracking is prevented in many cases and that spring back is removed are not yet fully understood. However, these phenomena are certainly related to the fact that explosive forming takes place in microseconds i.e. under extremely high rates of deformation. During the course of some work on the properties of materials after static and dynamic deformation, the writer observed a much finer and more diffuse slip when the metal was deformed by impact than when deformed statically in a press. This more uniform initiation and propagation of slip may be an explanation for the increased ductility of many metals under explosive loading. It is known that metals move in the die at 200 to 500 ft/sec compare to 1 to 5 ft/sec with conventional methods. Formulas have been obtained giving the relationship between static and dynamic ductilities of metals. Ratios of dynamic to static percentages of elongation for a few metals are as follows:

Nickel	1
Titanium	1.5
Carbon Steels	2.3
Aluminum	2.5
Magnesium	2.0
Tool Steels	2.0

However, no improvement in ductility has been obtained yet with the very brittle metals or alloys possessing elongations of 1 to 2 per cent.

The mechanisms by which the processes work also depend on the arrangement used. In the case of underwater forming there has been much talk as to whether the work was done by the gas bubble formed in the liquid medium, by the shock wave itself, or by the liquid medium pushed ahead of the shock wave. It is felt that the work on the blank is done mainly by the shock wave or stress pulse from the explosion. The fact that explosive forming under water is more efficient than in air is due to the better acoustic impedance match between water and the metal blank than between air and metal so that a greater amount of energy is transmitted. There should also be enough water to confine the charge properly. Different mechanisms may also act depending upon the distance if any, between the charge and the blank.

For a long time there had been evidence that metal deformed at high velocities with high rates of energy application (such as during the formation of a jet from a shaped charge liner) exhibited hydrodynamic behavior, i.e. deformed as a fluid or plastic. In such cases it is only when the velocity gradient between different parts of the piece is too great that fracture can take place. High pressures on the workpiece during deformation can prevent the formation of internal defects which would act as nucleus of fracture.

EXPLOSIVE FORMING IN THE MISSILE INDUSTRY

Many new techniques have been applied to the manufacturing of missile components, one of them being explosive forming (36, 44, 46, 47, 51, 67).

The Moore Co. of Marceline, Mo., has been explosively forming bulkheads for the Redstone Missile as subcontract from Chrysler Corporation. To form this hemispherically shaped part a 27-in. diameter by 0.270 in. thick, aluminum blank is placed on top of an open-end draw ring. Another thick steel sleeve is placed directly on top of the blank. The explosive forming is done under water using a 4 to 6 oz. charge of dynamite (46, 67).

Navy rocket nozzles have also been formed explosively by National Northern Corp. The nozzle is formed in two steps using 1020 steel. It is claimed that this steel, which has a normal elongation of 42 per cent, stretched 70 per cent under explosive loading (36).

The forming, sizing and straightening of rocket motor cases has been carried out by Propellex Chemical Corporation (44, 47, 51). The Terrier motor case is illustrated in Figure 2 after explosive sizing. This 11-ft long, 18 inches in diameter motor case is made up of heat-treated 4130 steel. An increase in yield strength of about 20 to 25 per cent was observed after explosive sizing. Very good tolerances with little spring back have been obtained. The Bomarc motor case 13 feet long by 3 feet in diameter has also been sized at Propellex, while a magnesium missile body for another missile has been explosively sized by the Nitroform Co.

Various other parts formed by Winchester Western Division of Olin Mathieson include:

Lox manifolded for Saturn missiles: .188 in. thick 5052 Al T-32 condition

Sound suppressors for the Boeing-707

Spark igniter guides

Jet engine diffuser cones of type 321 stainless steel

EXPLOSIVE FORMING IN CANADA

The considerable amount of effort devoted to high-energy-rate metal forming in the United States during the last few years has created great interest in Canada, and work along this line has been initiated both in research and development. Although the effort spent in Canada to date is only a small fraction of that spent in the U.S. some progress is being made in this field and the highlights are reported in this section.

FORMING

The Explosives Laboratories of Canadian Industries Ltd. have recently installed facilities for underwater explosive forming of metals.

Two setups have been used so far. A tank 18 in. in diameter and containing 2 ft. of water is used to form small test specimens about 6 in. x 6 in. A larger tank of 8 ft. by 12 ft. with a maximum depth of about 5 ft. of water is also available to form larger pieces. It is hoped to fire about one half pound of high explosives in it.

Figure 5 shows one of the specimens obtained in the small tank. The material is Type 321 stainless steel. It is embossed or corrugated by means of explosives as this method produces deeper corrugations than those obtained with a conventional press. Corrugating increases the rigidity of sheets for aircraft panels. One interesting aspect of explosive forming or of the bulging test at C.I.L. has been the direct correlation of the amount of bulging of a steel plate submitted to explosive shock with the comminution of rocks submitted to the same charge. So instead of counting the number of rock fragments and determining the increase in surface area of the rock after fragmentation with a new explosive, a test is carried out on a steel plate and the bulging of the plate is proportional to the amount of fragmentation of the rock.

Another research project has been initiated in Ottawa at the Physical Metallurgy Division of the Dept. of Mines and Technical Surveys. The main interest there lies in fundamental studies of the ductility or drawability and formability of metals under impulsive loading. A small closed vessel is used to deep-draw small sheets of metals in a free forming operation. Variables such as amount of charge, pressure, type of metal, thickness of blank, etc., are being studied.

A characteristic of the pressure vessel used is that it is completely leakproof and consequently noiseless. This is an advantage when explosive forming is to be carried out indoors, in a plant or a laboratory. Other aspects of this project in Ottawa also include the forming of shapes in closed dies.

C.I.L. maintain a staff of experts to advise industry on the use of explosives for high-energy-rate forming processes. Information may also be obtained on these processes from the Mines Branch, Ottawa.

In the industrial field, many firms have been active in experimenting with these new processes especially in the aircraft industry. At Avro Aircraft Ltd., Toronto, a cartridge actuated free floating piston has been used for piercing and dimpling sheets of titanium and other alloys for aircraft skins. In another firm, Bristol Aero-Industries Ltd., Winnipeg, components have been made of 3003-H14 Aluminum, to the shape, and using the arrangement shown in Figure 6. The forming is carried out under water by placing the assembly in a 50-gallon tank. The water head above the blank is about 2 ft. Concrete and kirksite dies have been used. Some crumbling was observed on the sharp corners of the concrete die where the metal was drawn over during forming. It is felt that a concrete die with steel inserts at these points should be satisfactory for production runs.

Kirksite dies were entirely satisfactory. It was also observed in this case that, probably due to the configuration of the die, a very high vacuum had to be used in order to prevent the piece from blowing backwards after the explosion.

The most active aircraft firm in this field has probably been Orenda Engines Ltd. of Toronto. Various shapes have been formed including air duct panels, cone frustums, fan blades, annular rings and turbine blades. The air duct panels were formed during the development of the Iroquois engine.

In forming air duct panels, the die, sheet metal blank and explosives are again immersed in water in a cylindrical steel tank 6 feet in diameter and 6 feet deep. The depth of water in the tank is about 4 feet. The materials formed were Types 321 and AM 350 stainless steels although titanium and aluminum alloys were also experimented. The dies used for various types of corrugations on air ducts were made of aluminum alloys. The largest die, which had an area of 5 square feet and a straightforward arrangement of 0.120 inch deep grooves, is the one shown in the arrangement of Figure 7 used to produce the shape illustrated in Figure 8. Dies for the other shapes are made of epoxy resin or of steel.

It was stated that the main difficulty in this work was in sealing off the water from the die, and various techniques were used to prevent the water from penetrating in the die cavity, between die and blank. Applications of silicone rubber or glyptol and linen tape, or simply of vinyl tape around the edge of contact between sheet metal and die were found successful. Another method which consisted in evacuating a polythene mylar bag placed around the die and blank produced excellent results.

The explosive was Primacord containing 50 grains of explosive per foot. Tests have indicated that under the conditions used about 6 to 10 feet of Primacord were necessary per square foot of 0.030 inch thick Type 321 stainless steel.

Explosive forming was found particularly useful when relatively deep and narrow grooves were required. There is some work-hardening produced, the Vickers hardness increasing from about 165 to 250.

Besides the aircraft companies, other firms have also been interested in explosive forming for parts such as pressure vessels heads, etc.

In this Establishment, work was continued on the forming of conical of hemispherical shapes by metal gathering (77). In this method, the free blank is accelerated towards the bottom of the die without being retained by a blank holder as in conventional method. This process, which results in a thickening rather than in a thinning out of the blank during forming, has been applied to larger and more complicated conical shapes such as shown in Figure 9. The forming is now carried out under water and variables such as amount of charge, stand-off distance, etc., can be varied to produce different shapes. Cones with cylindrical stems of various lengths have already been formed, and it is expected that step-like and bell-shaped cones could also be obtained. The materials used have been copper, stainless steels and aluminum alloys.

The mechanics of the deformation processes during forming have been studied by means of a grid scribed at the surface of the blank and by means of hardness and thickness measurements. Typical results obtained on the shape illustrated at the right-hand side of Figure 9 are shown in Figure 10.

On fully formed cones having a stem, the wall thickness of the cone is greater than that of the original blank all the way from the base to the stem. The process is thus entirely one of metal gathering. However, the deformation of the grid indicates that there is also a stretching of the material along the side of the cone. The metal gathering effect is thus great enough to compensate the stretching and to provide an overall increase in wall thickness.

EXPLOSIVE WELDING

Some experiments have been carried out on the welding of dissimilar materials by means of explosive pressures. Thin plates of 1100-0 aluminum, mild steel, stainless steel and galvanized iron were placed in contact with brass or copper plates 0.125 in. thick and 3.5 in. in diameter. A small pellet of explosive was placed at 3 in. above the assembly and detonated. The bonding was not very uniform in that it took place in patches. In the case of steels to copper, the sheets could be pulled apart although there was evidence of bonding and formation of a new compound at the interface. In the case of aluminum on copper, it was impossible to pull the aluminum off the copper as the aluminum sheet would tear around the bonded areas, indicating that the shear stress of the bond in this case was very high. Stainless steel-brass couples gave a shear stress of 17,000 psi.

The hardness of both components of each couple was also increased appreciably during the explosive bonding, the stainless steel for example increasing in hardness by 40 points Vickers.

Microscopic examination revealed new phases at the couple interfaces. In the case of the steel-brass couple, this phase could only be revealed when the specimen was etched with a copper etching reagent, indicating that the new phase was forming at the expense of the copper. In the case of the aluminum-brass couple the reverse was true, the new phase forming at the expense of the aluminum (see Figure 11).

The interesting feature of these tests is the presence of a layer of allowed material at the weld interface which indicates the existence of a real metallurgical bond between the dissimilar materials. There is some evidence that this layer forms at the expense of the material having the lowest melting point of the two materials in the couple.

When the joint could be pulled apart, the bonded patches showed fine ripple marks as illustrated in Figure 12 which indicate that the two surfaces to be bonded may not have been flat and parallel. It is felt that better surface preparation and the use of plane shock waves and underwater welding would result in better bonds. The rippling effect will be investigated to determine its effects on bond strength.

CONCLUSIONS

Explosives will be used increasingly as a source of energy for the forming, hardening, welding and processing of metals in general. It is difficult to predict the future of explosive forming in Canada although it is felt that the aircraft and missile industries will soon have to resort to it more extensively because of the new requirements in shape and materials to be formed. It is feared that underwater explosive forming may have its drawbacks during the severe Canadian winters due to below freezing temperatures lasting for an appreciable part of the year. The cost of heating the water pit, however, may not add very much to the overall cost of the operational although it might well be advisable to devise suitable methods of forming in air.

Forming by means of propellant cartridges, on the other hand, can be carried out indoors and it is claimed that the noise is not unbearable. Under certain conditions the operation can be made practically noiseless.

High-energy-rate forming can be applied to the production of a wide range of parts in terms of size, configuration, and material. It is hoped that the method will be used increasingly in Canada and that it may be applied with profit to the solving of problems peculiar to Canadian industries.

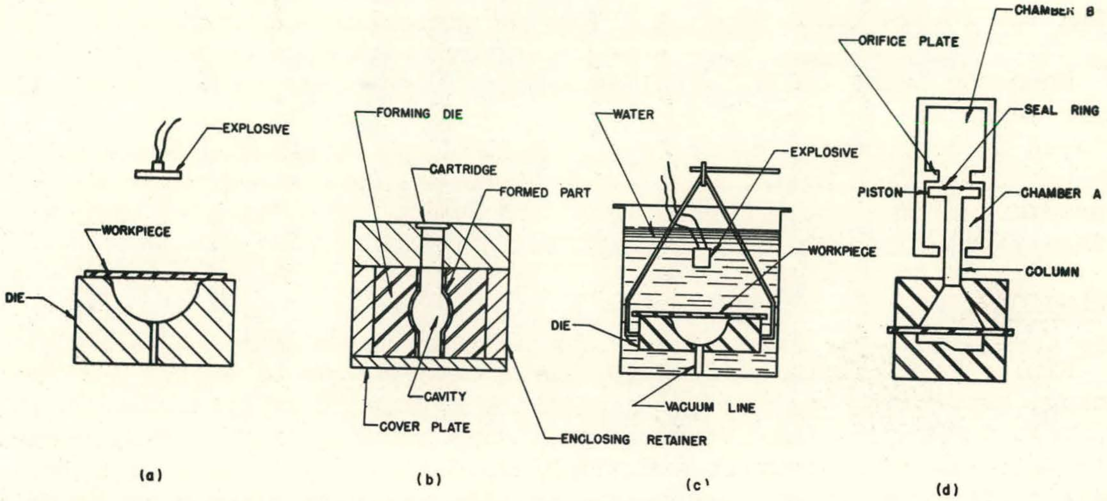


FIG. 1 – a) Explosive forming in an open die
b) Forming in a closed die by means of propellant gases
c) Explosive forming under water
d) Schematic diagram of a high-velocity press.

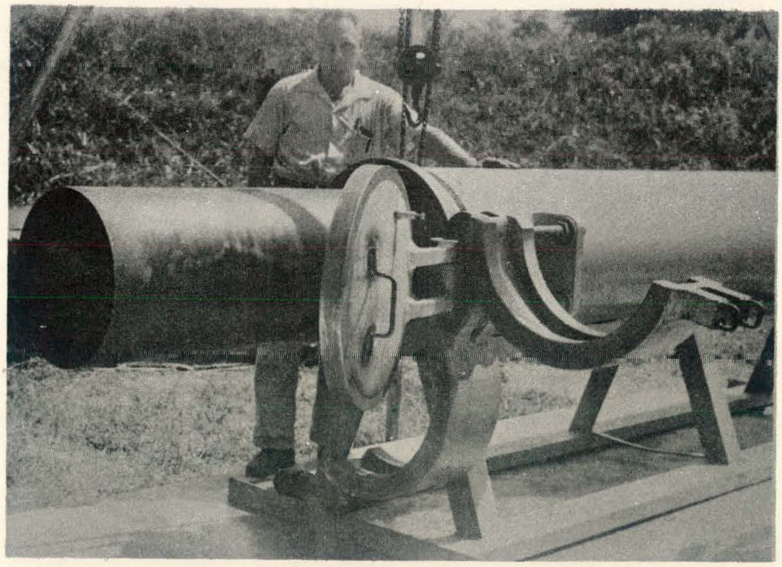


FIG. 2 – A 4130 steel rocket motor tube 11 feet long by 18 in. diameter shown partially inside the sizing die. This work is carried out by Propellex Corporation.

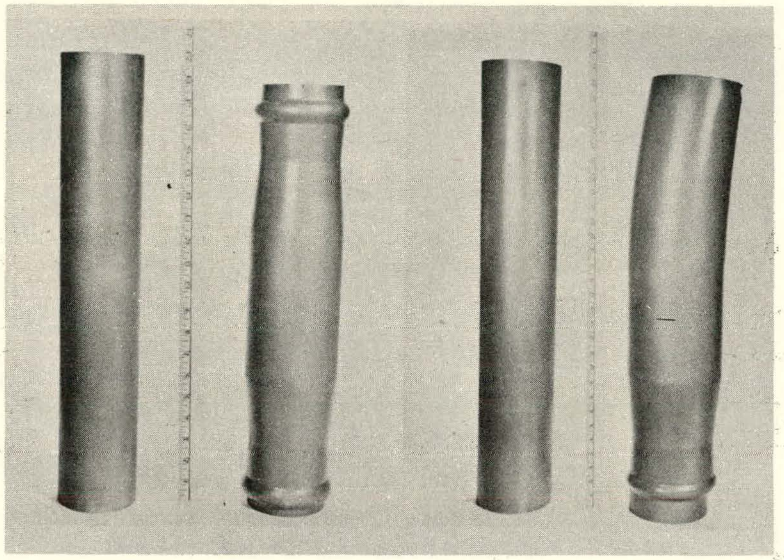
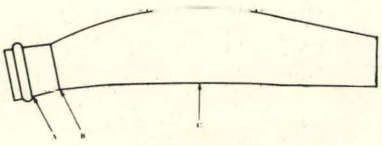


FIG. 3 – Explosively formed sound suppressor tubes for the Boeing 707 jet plane. These are formed by Olin Mathieson Chemical Corporation using the process shown in Figure 1 b.

Formed Part



Dimension Specifications

A 5.62 ± .010″ I.D.
B 5.41 ± .010″ I.D.
C 6.25 ± .030″ O.D.

Dimensions After Forming (From 25 Parts)

Location	*Average*	*Maximum*	*Minimum*
A (I. D.)	5.613″	5.622″	5.606″
B (I. D.)	5.407	5.422	5.399
C (O. D.)	6.227	6.260	6.200

FIG. 4 – Tolerances obtained on the sound suppressor tube shown on the right of Figure 3, after explosive forming.

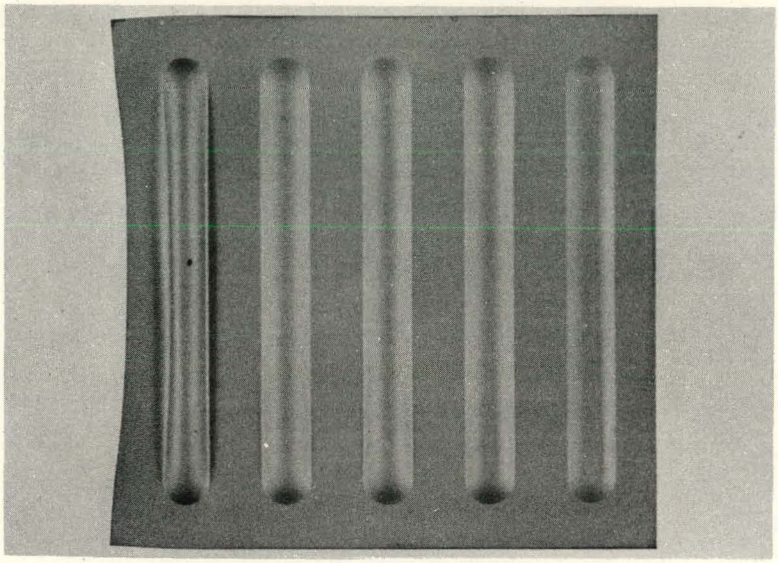


FIG. 5 – Explosively embossed sheet 0.35 in. thick of Type 321 Stainless Steel. Corrugations .080 ft. deep have been obtained by this method as compared with .050 in. deep on a press (Courtesy Canadian Industries Ltd.)

FIG. 6 – Arrangement for explosive forming of part at Bristol-Aero-Industries Ltd.

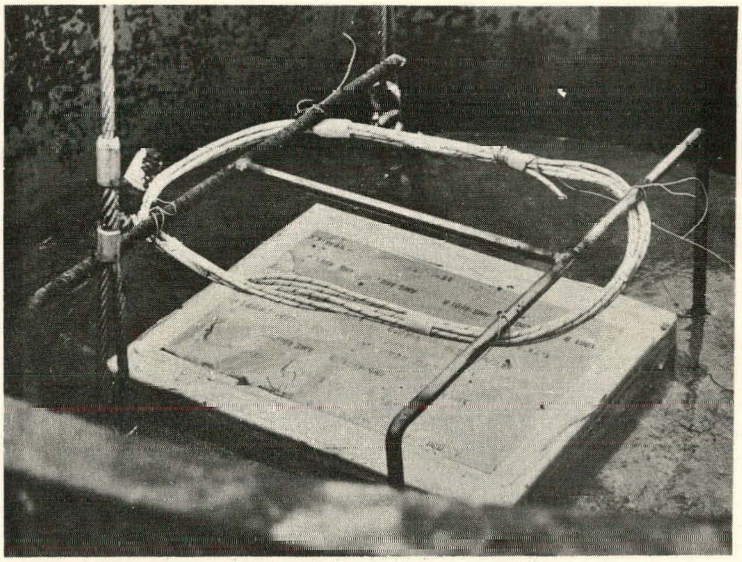


FIG. 7 – Arrangement for explosive forming under water of air duct panels for the Iroquois Engine. Shown are the die, blank and primacord charge (Courtesy Orenda Engines Ltd.)

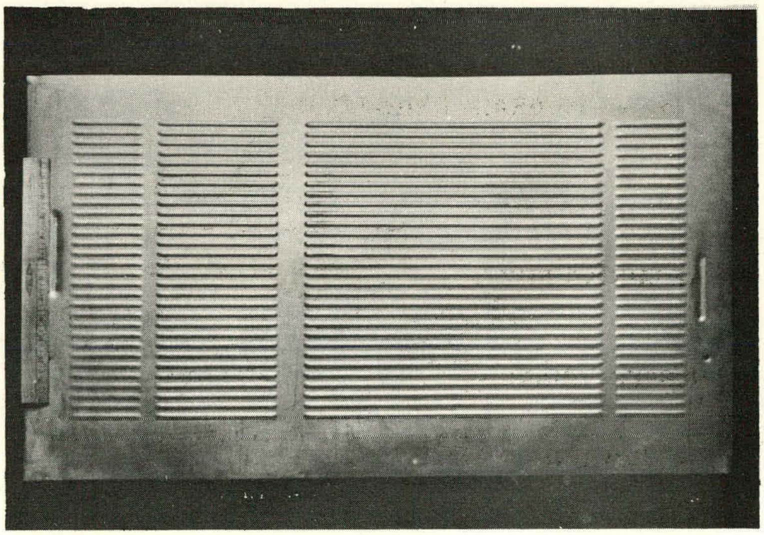


FIG. 8 – Explosively corrugated air duct panel (Courtesy Orenda Engines Ltd.)

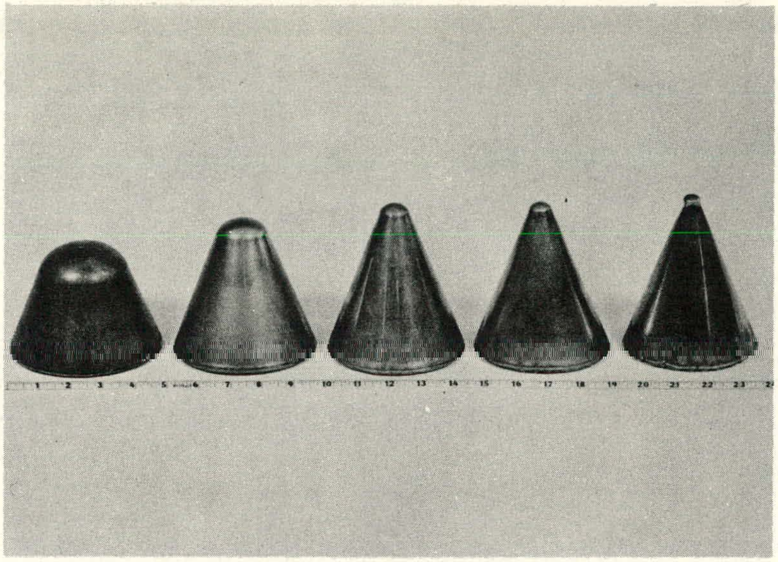


FIG. 9 – Various conical shapes produced by varying the amount of explosive and the stand-off distance.

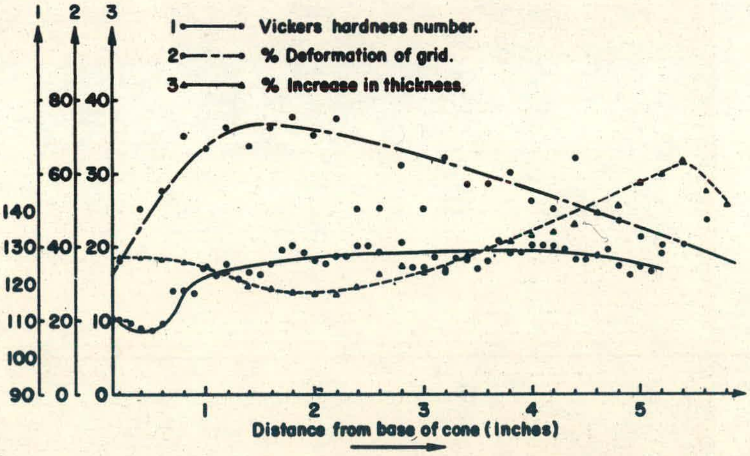
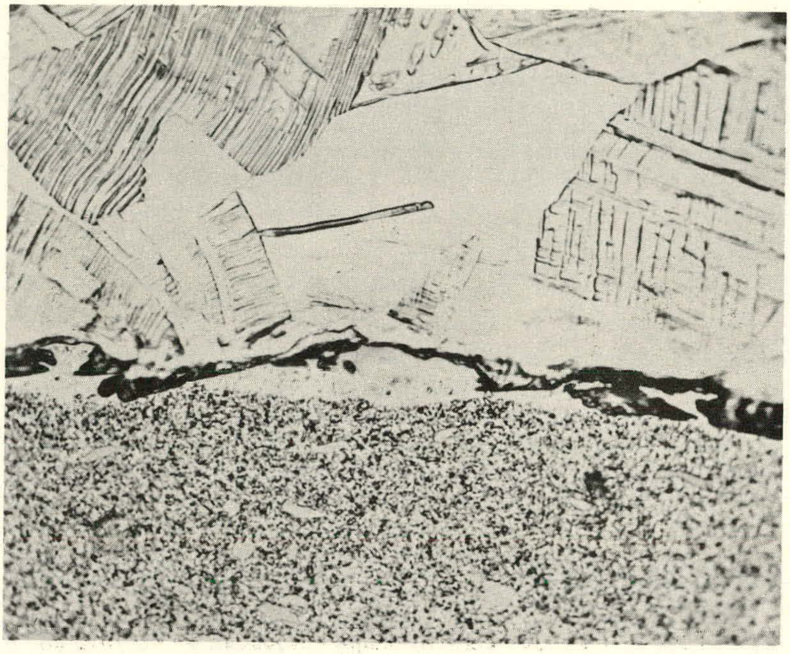
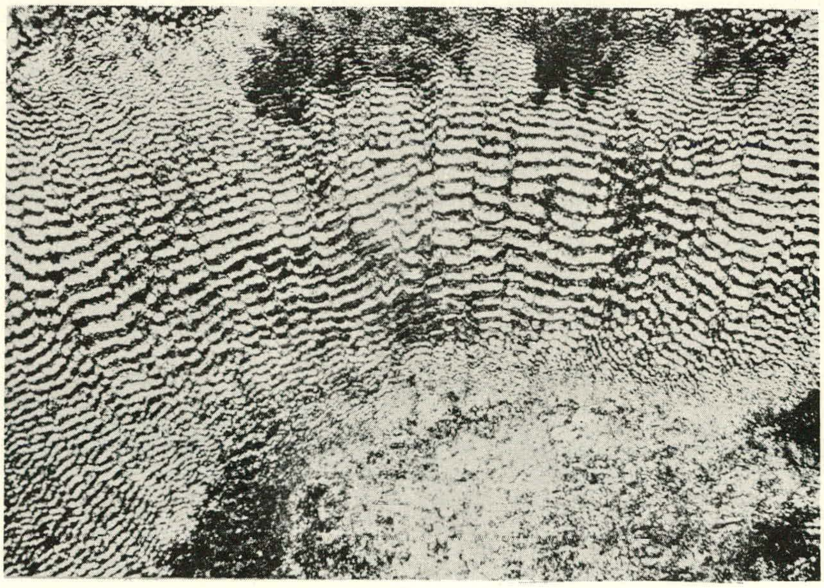


FIG. 10 – Hardness and deformation measurements along fully formed cone.



X1500

FIG. 11 – Illustrating the interface between the brass (top) aluminum (bottom) couple.



30X

FIG. 12 – Showing fine ripple marks at the brass-galvanized iron interface.

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