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review

OF RECENT
DEVELOPMENTS

High-Energy-Rate Processes

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INTRODUCTION

The Second International Conference of the Center for High-Energy Forming was held at Estes Park, Colorado, on June 23-27, 1969. The symposium was sponsored by the Army Materials and Mechanics Research Center and the Advanced Research Projects Agency. The proceedings were distributed prior to the meeting. A part of the Conference was concerned with the mechanics of high-velocity deformation or the effects of high-strain rates on the behavior and final properties of metals. The major part of the Conference dealt with innovations or details of various emerging processes, including equipment and processes under development in Europe and Japan. The apparent emphasis on descriptive presentations reflects the growing importance attached by the sponsoring agencies to transfer of research-and-development information to manufacturing organizations.

ELECTROMAGNETIC FORMING

Forming, sizing, and assembling of metallic parts by the action of pulsed magnetic fields are comparatively young processes. The action results from discharging electrical energy stored in a capacitor bank into a forming coil of appropriate design. During the discharge cycle, lasting typically on the order of 30 microseconds, induced magnetic fields develop pressures on conducting workpieces placed in or adjacent to the forming coil. System efficiency is important because the cost of capital equipment is approximately proportional to the amount of energy that can be stored in the capacitor bank. Coil design is very important because the coil must withstand the forming pressures for a usefully high number of cycles in repetitive operations.

Because of the complexity of the electromagnetic forming process, Lawrence used dimensional analysis to identify the importance of various parameters.⁽¹⁾ Eight factors of the electrical system and five parameters representing the properties of the workpiece were considered to be independent variables influencing energy requirements. The analysis lead to ten dimensionless functions that can be used in scale modeling calculations for electromagnetic forming operations. The analysis indicates that all energy values should scale in proportion to the volume of the workpiece. The efficiency of the process is expected to depend on a dimensionless number determined by the density of the workpiece and the capacitance, voltage, and inductance of the electrical system. The analysis should help in planning experiments to provide a better theoretical basis for the electromagnetic process.

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Jansen pointed out that the capacitor, coil, and workpiece should be considered as a system and be designed for optimum efficiency.⁽²⁾ Using a simplified mathematical model, he considered the effects of stored energy, frequency, and setup geometry on the efficiency, pressure, and deformation velocity in shrinking a metal tube by the electromagnetic forming process. The distance the surface of the workpiece moves before impacting the die (or "fly distance") is an important geometrical parameter. Higher efficiencies based on conversion of electrical energy to useful deformation are attained when the workpiece hits the die at the theoretical peak velocity, with no excess kinetic energy available for causing unnecessary impact stresses. The combination also will result in better coil and die life. The optimum conditions are achieved by proper combinations of fly distance, frequency, and kinetic energy. The computer simulation study, with a program based on some experimental data and reasonable assumptions indicates that lower frequencies and higher energies require larger fly distances. The cases considered show the effects of equipment limitations and forming parameters on efficiency. Some examples show that lower frequencies require smaller magnetic pressure to develop comparable peak velocities and kinetic energies. With some high-frequency conditions, the workpiece displacement is small enough so that the second pressure pulse contributes forming energy. Some of these conclusions based on Jansen's calculations are illustrated by Figures 1 and 2 and comparisons between them.

The design of external solenoid coils for shrinking or compressing workpieces was the subject of a paper by Gilbert and Lawrence.⁽³⁾ Very little information on the problem of coil design had been published previously. Their article shows how to calculate currents, fields, and forces for inductors and capacitors in the circuit from electromagnetic theory. This information permits assessing the capability of a particular installation on the basis of the maximum voltage and the capacitance of the equipment and the radius and length of the forming coil. The electromagnetic parameters determine the limiting mechanical forces that can be developed and that must be withstood by the coil. Equations are given which permit calculation of impulsive forces from the pressures and the pulse durations. Those forces must exceed the energy requirements for the forming operation of interest, taking efficiency into account, and must be considered in designing coils strong enough for a suitably long life in a particular application.

Sometimes coils other than the simple spiral and solenoidal types are of interest, and, in this

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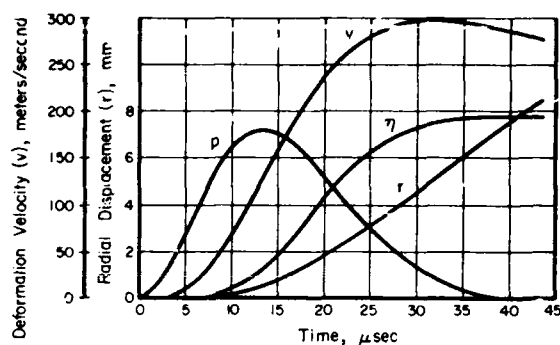


FIGURE 1. VARIATIONS IN DEFORMATION VELOCITY (v), RADIAL DISPLACEMENT (r), MAGNETIC PRESSURE (p), AND EFFICIENCY (η) WITH TIME FOR ELECTROMAGNETIC FORMING OF A C1015 STEEL RING(2)

(f = frequency of circuit, E = stored energy, C = capacitance of storage bank)

regard, Al-Hassani, Duncan, and Johnson presented approaches for designing several variations of the basic types of coils.(4) Their experimental techniques should help in designing coil windings that cause pressure distributions suitable for particular applications. The pressure distributions can be controlled by altering the coil configuration and the electrical circuit to adjust the shape and magnitude of the pressure pulse. They recommend the use of search coils and of multiple dimpling operations on thin sheet as alternative methods for measuring pressure distributions produced by prototype or preliminary coil designs. The dimples were formed in an array corresponding to a grid pattern covering the area of interest. The depth of a dimple is a measure of the pressure at that location. The use of the two techniques was illustrated by experiments with four different types of flat coils.

Figure 3 shows the effects of using two different types of flat-coil designs on the instantaneous profiles of diaphragms formed freely in air. The aluminum sheet used for the experiments was 0.035-inch thick and the discharge energy was 0.36 kJ. The coil designs are shown above the appropriate charts. With the conventional coil design shown at the left, the peak pressure occurred at a (non-dimensional) radius of 0.6. The material at that distance moved away from the coil more rapidly than from the central region. Later, the material at the center formed the apex. The coil at the right, with the inner turns in a direction opposing those near the outside, developed two pressure peaks (at radii of 0.4 and 0.8), and caused the workpiece to move uniformly.

Although electromagnetic techniques are most widely used for assembly operations and for forming thin sheet or tubular stock, Blanc and Dekergand described operations on Saturn 1-C bulkheads(5) These elliptical welded structures have major and minor diameters of 33 and 11-1/2 feet, respectively. They must meet dimensional tolerances of 2 or 3 degrees on the outside contour and of 0.05 inch on weld mismatch. The structures are made from 2219-T86 aluminum alloy with weld-land thicknesses ranging from 0.22 to 0.46 inch. Equipment for correcting weld distortion included special coils for use with a portable 18 kJ capacitive discharge unit.

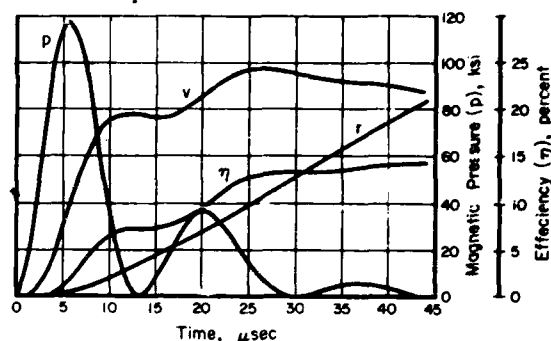
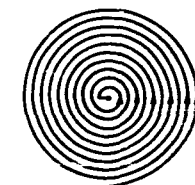


FIGURE 2. VARIATIONS IN DEFORMATION VELOCITY (v), RADIAL DISPLACEMENT (r), MAGNETIC PRESSURE (p), AND EFFICIENCY (η) WITH TIME FOR ELECTROMAGNETIC FORMING OF A C1015 STEEL RING UNDER CONDITIONS INDICATED(2)



45 in OD, 0.5 in ID, 28 turns



45 in OD, 0.5 in ID, 28 turns
(inner turns opposite direction)

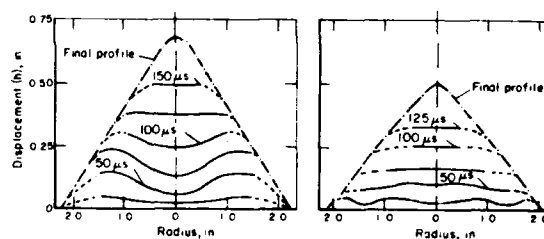


FIGURE 3. EFFECT OF COIL DESIGN ON UNIFORMITY OF BULGING IN FREE FORMING BY ELECTROMAGNETIC PROCESS(4)

(0.035-inch-thick aluminum sheet, energy = 0.36 kJ)

The techniques developed for this specialized electromagnetic forming operation allowed the dimensional specifications to be met. No damage to the welds was detected by X-ray and dye-penetrant inspection.

ELECTROHYDRAULIC FORMING

The electrohydraulic process, which harnesses for useful purposes the energy released by the discharge of a high-voltage spark under water, is probably the most widely applied high-energy forming method. To simplify manufacturing operations, the spark is usually discharged between permanent electrodes rather than by exploding a wire, as is sometimes done in experimental studies. Equipment for electrohydraulic forming includes a power source (electrical energy stored in a bank of capacitors), forming dies, a press to open and close the dies, and provisions for filling the cavity with water and for evacuating air from between the die and the workpiece.

Over a million parts have been produced by electrohydraulic forming which are used on every jet transport plane now in production according to Cadwell.⁽⁶⁾ The equipment and process, trademarked "Soniform" by Rohr Aircraft, is used for forming more than 300 different precision parts for the aerospace industry. The more common type of unit operates horizontally and semiautomatically. The operator loads the part, closes the die, and starts the cycle. Dual-die actuating units utilize a single power supply. The forming process is most attractive, economically, when it forms parts which are ordinarily assembled from two or more stampings.

Shimadzu Seisakusho, Ltd., also is marketing electrohydraulic forming equipment.⁽⁷⁾ A horizontal unit is used mainly for tubular work; the vertical unit is preferred for sheet-metal parts. The horizontal unit will take tubular workpieces up to 8 inches in diameter and 14 inches in length. The total discharge voltage of the 45 kJ units is 30 kv and the frequency is about 20 kHz.

A wide variety of parts have been made in small lots. For instance, copper sheet has been formed into complex electrodes for electrodischarge machining of molds and die cavities. Some ingenious techniques have been developed; one is illustrated in Figure 4. In this approach, both fixed and movable dies are included in the assembly. As the impulsive pressure is transferred by the fluid to the inside of the pot, pressure is also applied to the movable die to produce axial motion. This compensating compressive stress should minimize wall thinning and increase the permissible circumferential strains before rupture.

In order to overcome the disadvantage of relatively long cycle times, the possibilities of forming many parts simultaneously have been studied. One approach used for mass producing automotive parts is to incorporate several die sets in one discharging chamber. This increases production rates without shortening the time needed for a single shot.

Inoue and Nishiyama used high-speed photography to study the mechanisms for transmitting energy liberated by an underwater electrical discharge to the workpiece.⁽⁸⁾ Like earlier workers, they concluded that the principle is the same as in explosive forming. The initial deformation results from a primary shock wave; a second deformation results from the action of the gas bubble formed by the electrical discharge. Since the latter effect is important, the efficiency of the operation can be improved by utilizing the interaction of gas bubbles formed by two successive sparks. Both the time interval between sparks and the electrode spacing are important, and there is an optimum electrode spacing to achieve the maximum amount of bulging.

EFFECTS OF HIGH-ENERGY-RATE FORMING ON PROPERTIES OF MATERIALS

The microstructure of pure polycrystalline nickel subjected to explosive shock loading and subsequent heat treatments by transmission electron microscopy was studied by Trueb.⁽⁹⁾ Shocking at 70 and 320 kb developed substructures resembling those normally caused by cold work. Heat treating for short times in the range from 600 to 780 C (1110 to 1435 F) caused recovery by dislocation migration; no polygonization, nucleation, or grain growth was observed. Shocking nickel at 1000 kb, on the other hand, developed an extremely high density of dislocations, clusters of point defects, and complex pat-

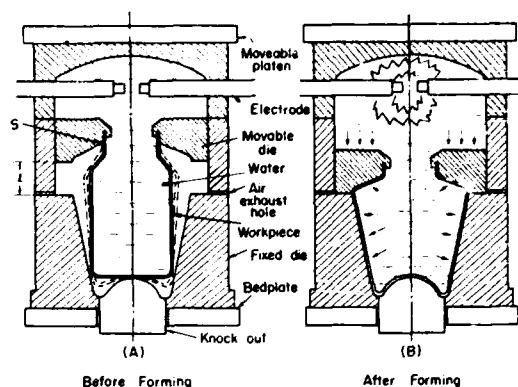


FIGURE 4. TUBULAR PART FORMING BY MOVABLE DIE ASSEMBLY TECHNIQUE⁽⁷⁾

terns of microtwins. Subsequent heat treatment for times of less than 6 minutes at 600 or 780 C developed comparatively low hardnesses. The heat treatments caused nonuniform polygonization, nucleation, and grain-boundary migration. Recovery caused by shock-induced heating also occurred on a highly localized scale in the specimens subjected to the higher intensity shock pressures.

Several papers dealt with the effects of high strain rates on the behavior of metals during deformation and on their final properties. Four types of steel were tested by Van Wely at temperatures ranging from 20 to -196 C (68 to -321 F) and at strain rates ranging from 0.025 to 2000/second.⁽²⁹⁾ The influence of strain rate on the limiting values for uniform elongation was not the same for uniaxial and biaxial straining. In uniaxial tension, the uniform elongation values for Type 304 stainless steel, N-A-TRA 70, and N-A-XTRA 100 increased with strain rate. In similar tests, strain rate had no effect on the ductility of a low-carbon steel. In bulge tests, the limiting pole strain for the low-carbon steel decreased with strain rate; the limits for the other steel were independent of deformation rate.

Techniques for determining dynamic stress-strain/strain-rate relationships for metals by expanding-ring experiments were described by Hoggatt and Recht.⁽¹⁰⁾ The ring used for the specimen is shrink fitted over a hardened steel core that transmits the shock generated by a chemical explosive. The explosive charge is centrally located in the steel core. As indicated in Table 1, all of the metals exhibited higher flow stresses at high strain rates than they did in conventional-speed tensile tests. Softer or weaker metals were more sensitive to fast straining rates. In the cases of aluminum and normalized 4130 steel, the dynamic yield strengths were doubled by strain rates exceeding 500/second. For all materials investigated, strain-rate effects were more noticeable in the range below 500/second than at higher strain rates. Usually, a single stress-strain curve would represent the behavior of a metal within 5 percent for strain rates varying from 500 to 15,000/second. Except for the titanium alloy, the strain at rupture was higher in dynamic than in static testing. Presumably, this reflected the fact that necking did not occur, hence all deformation occurred as uniform strain.

The effects of conventional and of explosive forming on the tensile and hardness properties and

TABLE 1. STRAIN-RATE SENSITIVITY OF MATERIALS TESTED IN EXPANDING RING EXPERIMENTS⁽¹⁰⁾

Material	Type	Condition	Static Yield Strength, ksi	Strain Rate, sec ⁻¹	Ratio of Dynamic to Static Yield Strength
Aluminum	2014	Annealed	14	500-7,000	2.0
Steel	4130	Normalized	61	500-9,000	2.0
Titanium	6Al-4V	Forged	136	500-15,000	1.4
Steel	4130	HT-R _c 31	122	500-11,000	1.3
Steel	4340	HT-R _c 39	156	500-13,000	1.2
Steel	D6ac	HT-R _c 49	254	500-9,000	1.1

the response to heat treatment of 2014 aluminum alloy were compared by Orava and Otto.⁽¹¹⁾ They found no differences in the final microstructure, hardness, strength, work-hardening rate, or ductility that could be attributed to differences in forming rate. Figure 5 shows the response to aging at 350 F of solution-treated 2014 aluminum. The scatter bars cover the range in hardness exhibited by materials representing three conditions before solution treatment: unformed, rubber pressed, and explosively deformed to strains of 0.11 and 0.16 inch/inch.

The stress-corrosion behavior of explosively formed 2014 aluminum alloy was investigated by Whiting and Orava.⁽¹²⁾ They concluded that deformation, regardless of strain rate, did not impair the relatively good resistance of the 2014-O grade to stress corrosion in 3.5 percent aqueous solutions of NaCl. The data also suggested that explosive forming has a less detrimental effect than does conventional forming on stress-corrosion characteristics of material formed in the -T6 condition.

Meager data presented by Mikesell suggest that strain rate had little or no statistically significant effect on tension-tension fatigue properties of 2014 aluminum deformed in the -T6 condition.⁽¹³⁾

An extensive study on explosive strengthening of steels was summarized by Mykkanen, Doherty, and Henriksen.⁽¹⁴⁾ Some of the work was concerned with precautions required to prevent spalling and to control the pressures and time durations of the pressure pulses. The effects of wave reflections and interactions were also discussed in the paper. Pearlitic, martensitic, stainless, and maraging steels were included in the experimental programs. Noticeable increases in strength were achieved by explosive hardening. For instance, shocked specimens of 4340 steel exhibited yield strengths 30 to 70 ksi higher than those expected from conventional heat treatment. The ultimate strengths were on the order of 25 ksi higher after explosive shocking. These benefits were achieved at the expense of some decreases in ductility and toughness as measured by tensile elongation and by impact values. The explosive-hardening treatments were apparently performed after quenching and before the tempering operation.

MECHANICS OF HIGH-ENERGY-RATE METALWORKING

Attention is being given to the measurement problems posed by the short time intervals characteristic of high-velocity forming. Bouma described techniques for measuring strain-time history in the plastic region during explosive free forming of

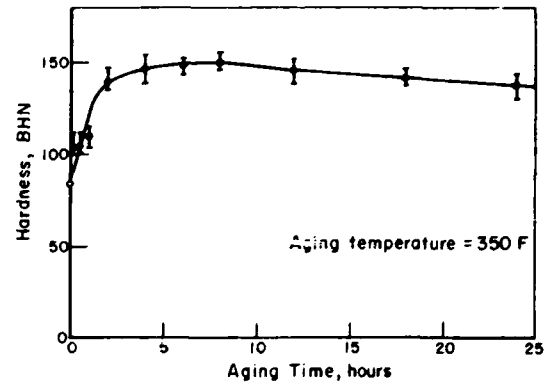


FIGURE 5. ISOTHERMAL AGING CURVE FOR 2014 ALUMINUM ALLOY SUBSEQUENT TO SOLUTION TREATMENT OF UNFORMED, EXPLOSIVELY FORMED, AND RUBBER PRESSED 2014-O⁽¹¹⁾

metal blanks under water.⁽¹⁵⁾ Electrical-resistance strain gages with backings of polyimide and filled epoxy worked satisfactorily. Elongations up to 11.5 percent were measured at strain rates up to 100/sec without gage failures. The time-displacement history displayed on an oscilloscope was recorded photographically. A paper presented by Samanta and Magi dealt with instrumentation for high-velocity upsetting of specimens at temperatures from 80 to 1470 F.⁽¹⁶⁾ Ram velocities ranged from 164 to 328 feet per second in the experiments. Forces were measured by strain gages mounted on a pressure bar in series with the specimens, and displacements were measured by a photometric system.

The deformation process of explosive forming of thin-walled circular rings was analyzed by Ching and Weese.⁽¹⁷⁾ The strains were considered from the standpoints of both energy transfer and of pressure loading. The analytical results agreed well with data from experiments at various charge weights of PETN on 6061-7C tubing. Equally good agreement was obtained for predictions based on pressure analyses. Because the calculations are cumbersome, two design curves were presented for use in predicting maximum and final strain resulting from various charges.

Formability limits in producing hemispherical disks without a draw ring was the subject of a paper by Burnham, Norris, and Cossa.⁽¹⁸⁾ In this approach, radial compressive stress is induced during the early stage of forming by using a gather ring on top of the die. The use of a blank holder in the alternative approach produces radial tensile stress in the flange of the workpiece. The forming limits in gather forming are set by buckling and by fracture. The limits depend on the rigidity of the starting blank, the ductility of the workpiece, the shock coupling process, and deformation strains. The gather-forming process was analyzed using the principle of mass conservation and an assumed function of wall thickness. Predicted and measured strains were generally in good agreement. Equations for calculating deformation energy, explosive energy delivered to the blank, and some causes of buckling were also checked by experiment. The elastic buckling limit for disks of 6061-O aluminum was found to correspond to a diameter/thickness ratio of 130. Much higher buckling limits can be achieved by using sandwich techniques for explosive gather forming.

Explosive punching of multiple holes, simultaneously, in tubular specimens was studied by Harding, Kulkarni, and Larralde.⁽¹⁹⁾ Water was used as the transfer medium between the line charge of explosive and the workpiece, which was confined by dies containing holes of different diameters. The tubes were 8 inches long with 2-1/8-inch OD and 2 inch ID; the holes were 1/4, 3/8, 1/2, and 5/8 inch in diameter. Charge weights of PETN as low as 125 grains per foot were sufficient to punch 1/4-inch-diameter holes in high-strength steel. As a result of an analysis of the punching process made during the study, an empirical formula was developed for estimating the energy requirements of explosive punching.

Explosive punching of holes in high-strength steel plates was theoretically and experimentally investigated by Howell and Dowling.⁽²⁰⁾ Shaped charges were used to cut 2-inch-diameter holes in 3/8-inch plates. Both standoff distance and the wedge angle of the shaped charge had marked influences on the hole penetration or efficiency, and the wedge angle also affected the shape of the groove cut in the plate. The authors concluded that penetrations greater than 0.5 inch per shot should be possible and that the operation is feasible for use in the field.

Tube bulging experiments, which confirmed earlier theoretical analyses of the deformation of thin cylindrical shells under radial impulsive pressures, were conducted by Masaki.⁽²¹⁾ The experiments were conducted on annealed copper (1.2-inch OD, 0.04-inch wall) with an exploding wire device. High-speed photographs showed that the center of the shell was first displaced uniformly in a radial direction and then by bending waves that started at reinforcing rings and traveled toward the center. The analysis also was extended to larger strains by making several basic assumptions. Some of the more important assumptions were that (1) the duration of the pressure pulse is short compared with the termination period of deformation, (2) the displacement of the tube wall under radial pressure is small compared with the final displacement, and (3) the material is perfectly plastic. Much of the deformation and the shape of the final profile were attributed to the effect of bending waves propagating from restraining or reinforcing rings at the end of the tube. Equations were presented for predicting the profiles of bulged cylindrical shells.

HIGH-ENERGY-RATE METALWORKING

In addition to the electrical systems mentioned earlier, chemical explosives and other energy sources have been used for a variety of metal processing operations.

An intensive investigation on high-energy metal forming and auxiliary operations has been in progress at the University of Birmingham since 1965. A paper by Tobias and associates gave the highlights of studies which had been reported in detail in 24 earlier publications.⁽²²⁾ Much of the work has been concerned with the design and development of suitable equipment. The devices consisted essentially of a power cylinder (comparable to an internal combustion chamber) integrated into a press frame. The power cylinder could be fueled by diesel oil, gasoline, mixtures of those liquids, or propane. Using such equipment was said to lower capital costs by 15 percent compared with mechanical-pneumatic devices. Ram speeds were about 50 feet per second maximum, and output energies ranged from 5,000 to

20,000 ft-lb. One slow-speed machine had been built to deliver 20,000 ft-lb at a ram velocity of 17 feet per second. Designing a machine for such a speed, which is in the range for conventional drop hammers resulted in higher cost and heavier equipment than would be needed for a machine with a higher velocity. A 75,000-ft-lb counterblow machine with a relative platen speed of 80 feet per second operated with a cycle time of 12 seconds. The "Petro Forge" devices can deliver a number of blows in quick succession like a hammer. Such energy-limited devices can deliver a large total amount of energy compared with single-stroking presses of comparable size and cost.

Theoretical and experimental work indicates that high-velocity cropping (bar shearing) may offer advantages in commercial operations.⁽²²⁾ Increasing the blade velocity from the conventional level of approximately 0.5 foot per second to the 8-to-60-feet per second range produces sheared surfaces more nearly perpendicular to the bar axis and relatively free of defects. The improvements were most noticeable in the case of steel and aluminum, but were negligible for the titanium alloys, manganese bronzes, and nickel-base alloys investigated. Plant studies with a high-velocity bar-cropping machine are to start soon. Blanks produced from sheet metal at high shear velocities usually exhibit better cut surfaces; most nonferrous metals do not. Figure 6 shows that the amount of distortion, evidenced by doming and dishing of the blanks, is also affected by shear velocity. Those data for mild steel suggest that the optimum blanking velocity lies within the range from 30 to 40 feet per second. Other data indicate that the peak load developed during blanking occurs earlier in the stroke and reaches a higher level in high-velocity blanking operations.

The "HYDROPUNCH" which is a pneumatic-hydraulic device for metalworking was described by Tominaga and Takamatsu.⁽²³⁾ In this device, compressed air operates a hammer that plunges into a chamber filled with water and generates a high pressure in the fluid. The hydraulic pressure is transferred by the water to the surface of the workpiece that has been placed in a die set and forms a part

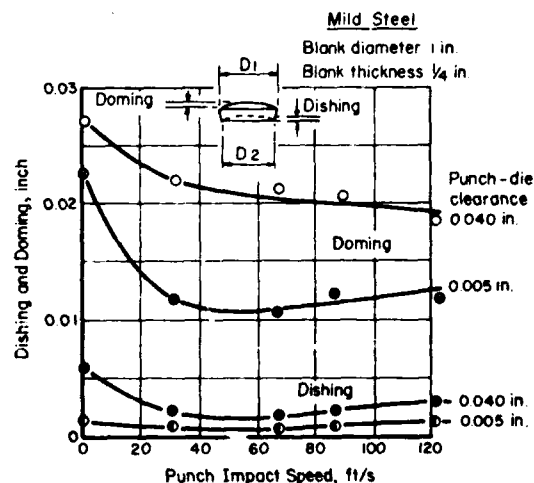


FIGURE 6. EFFECT OF PUNCH VELOCITY ON DISTORTION OF BLANKS SHEARED FROM MILD STEEL SHEET⁽²²⁾

within a time interval of several milliseconds. The equipment has been used to form a variety of tubular, cup-shaped, and disk-shaped parts and V-belt pulleys as test samples, and some products are being produced in large quantities.

High-velocity extrusion-molding experiments were described by Dower.⁽²⁴⁾ This technique consists of extruding a heated billet at a high velocity into a closed die. The operation resembles a die casting except that the workpiece is solid rather than liquid when it contacts the die. The experimental work was carried out in a subpress actuated at a ram velocity of 37 feet per second by a drop hammer or a pneumatic-mechanical machine. The momentum and plasticity of the hot workpiece results in filling even intricate die cavities. Traveling at a high velocity resulting from the fast ram speed and a heavy extrusion reduction, a heated billet fills the die by a combination of buckling and upsetting deformation. For a given impact energy, best results were obtained by using hotter billets for smaller extrusion ratios. For example, in studies on alpha-beta brass, good results were obtained on billets heated to 1425 F and extruded at a ratio of 41 and on billets heated to 1740 F which were extruded at a ratio of 11. Tests have also been conducted successfully on gray iron, nickel-base alloys, and various grades of engineering and stainless steel.

Procedures for explosive forming elliptical domes (0.7 elliptical ratio) from quenched-and-tempered HY 140 steel were described by Blanc.⁽²⁵⁾ A Kirksite die with a clamped blank holder was employed for multiple shots on blanks 48 inches in diameter and 0.345 inch thick. In the first operation, a buffer of 1-inch-thick rubber was used to minimize a slight tendency for conical deformation. It was protected by a thin (0.060-inch) sheet of mild steel. In the subsequent shots needed to reach the desired depth/diameter ratio of 0.33, water was used as the medium for transferring energy from the Primacord explosion to the workpiece. Forming in air rather than during immersion in a water tank simplified operations. Nevertheless, the high cost of large dies and the relatively long processing times necessitate careful study before adopting explosive forming as a production process for high-strength steels.

Kiyota and associates presented information on using a driver plate to impact and form a sheet workpiece.⁽²⁶⁾ Energy generated by detonating an explosive was transferred to the driver plate through a bath of water in a closed pressure vessel lead, vinyl plastic, and aluminum plates ranging in thickness from 0.004 to 0.02 inch were used in the experiments. Best results in forming 0.016- and 0.012-inch-thick austenitic stainless sheet were obtained by using 0.016-inch-thick aluminum sheet for the driver. The technique is said to give better reproduction of die details than conventional methods. Because the blank is free during forming (no blank holder), formed parts deform less during trimming. The procedures were used successfully for making denture plates from stainless steel.

Autofrettage strengthens hollow cylinders by producing residual compressive stresses at the bore. The technique usually consists of applying an internal pressure sufficient to expand the inside surface plastically while developing only elastic stresses near the outside surface of the cylinder.

The possibility of using explosive autofrettage techniques for strengthening gun barrels was discussed by Colton and Jones.⁽²⁷⁾ Currently, hydraulic techniques are used on a number of Army cannons such as the 175-mm long-range artillery piece. Experiments were conducted with 4340 steel tubes of 2.5-inch OD x 1.125-inch ID using Primacord (32 grains per inch). No detrimental effects of explosive working were noticed on microstructure or mechanical properties. The free-forming studies were said to indicate that explosive autofrettage is feasible from both an economic and a technical standpoint. Since the amount of deformation desired at the inside diameter is small, explosive shock intensities need not be excessive. So far, spalling has not been troublesome and retaining dies have not been necessary. Hydraulic autofrettage requires expensive pumps and dies. Capital costs for explosive autofrettage will be much lower if dies or momentum traps are not needed to prevent spalling or end effects.

The explosive compaction of powders into axisymmetrical shapes was the subject of a paper by Leonard, Laber, and Linse.⁽²⁸⁾ The powders were vibratory loaded into steel tubes 1-1/2-inch OD by 1-3/8-inch ID by 8 inches long. After evacuation to approximately 0.01 torr, the ends of the tube were sealed. Then, a granular explosive was compacted uniformly between the tube and a cardboard container. Detonation from a central point at one end produced a cylindrically uniform detonation front traveling down the length of the tube. The detonation velocity was approximately 9700 feet per second.

The types and characteristics of the powder materials used for the experiments are listed in Table 2. The explosive loading that produced compact densities greater than 97 percent of theoretical levels without defects attributable to excessive pressures are also given in the table. The wide range in explosive required per unit weight of different powders is attributed to the variation in compressive strength of the materials studied. The relationship is linear. The results suggest that data on loads needed for densifying any two materials with specific explosives, on container dimensions, and on sample sizes would provide a useful guide for estimating the explosive load needed for compacting other powders.

TABLE 2. TYPES AND CHARACTERISTICS OF POWDERS USED FOR EXPLOSIVE COMPACTION⁽²⁸⁾

Characteristic	Type of Powder				
	Al ₂ O ₃	Tungsten	Ti-6Al-4V	B-1900	Nickel
Particle Size, mesh	-325	-325	+100	-40	-325
Loading Density, g/cc	1.07	4.83	1.68	5.59	3.64
percent of theoretical density	29	25	38	68	41
Conditions for Complete Densification					
Powder Weight, (a) grams	209	936	334	1084	708
Explosive Weight, (a) grams	1040	1172	380	1106	579
Weight Ratio, powder/explosive	0.20	0.80	0.88	0.98	1.22

(a) Weight per 8-inch-length, 1-3/8-inch-ID steel tube used to contain the powder. The explosive was granular dynamite packed to a density of 1 g/cc with a detonation velocity of approximately 9700 feet/second.

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7

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