HYPERPLASTICITY: ENHANCED FORMABILITY OF SHEET METALS AT HIGH WORKPIECE VELOCITY

DISSERTATION

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By

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ABSTRACT

High velocity sheet metal forming was the focus of much research approximately 30 years ago, but has become somewhat dormant since then. Initially developed for fabricating big components, their use continued for the manufacture of small components of intricate shapes as well. However, their potential to improve formability was poorly understood.

In the current investigation, electrohydraulic forming was used to generate high workpiece velocity. Electrical energy up to 50 kJ was stored in a bank of capacitors and was discharged rapidly across a pair of electrodes under water. This generated a high intensity shock wave which forced the sheet metal into a die. Comparative conventional forming was done by pressurizing the oil beneath the workpiece with a hydraulic pump.

Formability increase of over 400% was observed on 6061 T4 Aluminum sheets and an increase of over 150% on interstitial free iron and OFHC copper. Limit strains were directly measured on the samples. Forming Limit Diagrams were used to compare low and high rate results. The estimated metal velocities at high rates ranged from 130 m/s to 350 m/s and the strain rates were of the order of $10^3$ s$^{-1}$. 
At such energies and time scales, inertial forces act to diffuse the deformation away from the localized areas, thus postponing the failure. Compressive stresses generated by the impact of sheet with the die wall also increase the ductility. However, the strain rate appeared to be still too low to cause adiabatic localization that might have limited the formability. The estimated velocity was also much lower than the von Kármán critical velocity for localization. The terminal hardness of finished components differed from the initial hardness within 20%. Thus, the material constitutive behavior did not appear to have changed.

Increased formability makes these high rate processes competitive to traditional superplastic forming. In order to distinguish this effect from superplasticity, the current phenomenon is termed *hyperplasticity*. 
Dedicated to
Mrs. Lakshmi and Dr. D. Sundararaman
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CHAPTER I

HIGH VELOCITY FORMING TECHNIQUES

High rate processes derive the name from the high work piece velocities characteristic of them. All the high rate processes have the common feature of rapid release of energy to the workpiece over a few microseconds, thus accelerating the workpiece away from the energy source to high velocities (typically 20-300 m/s) considerably greater than that attained in conventional processes.

High rate forming processes can be classified under the following categories:

- Explosive forming:
- Gas mixtures forming
- High voltage discharge forming
- Pneumatic-Mechanical forming
- Pneumatic-Hydraulic forming

These processes are in use since the early 1950s and have been referred to in many ways in the literature. They were called High Energy Rate Forming (HERF) processes, owing to rapid release of energy involved in all of them.
Since energy rate can mean power, all high-power forming processes could also be classified under this name. However, since that was not the distinguishing nature of these processes from others, "High Velocity Metal Forming" was used by some people to bring out the high workpiece velocities characteristic of these processes. One can also find in the literature terminologies such as High Strain Rate Forming, High Energy Release Rate Forming and High Rate Forming.

1.1 Explosive forming:
In explosive forming chemical energy from the explosives is used to generate shock waves through a medium (mostly water) which are directed to deform the work piece at very high velocities. The explosive working of materials can be divided into two main groups, stand-off and contact, depending upon the position of the explosive charge relative to the workpiece. This can result in large differences in energy requirements and consequently difference in mechanical behavior of the workpiece.

1.1.1 Stand-off operation:
In a stand-off operation, as shown in Figure 1.1, energy is released at some distance from the workpiece and is propagated mainly in the form of pressure pulse through intervening medium, usually water. Peak pressures at the workpiece range from several GPa to several hundred GPa, with most operations performed in the lower pressure area [1]. The working times are normally measured in milliseconds and the workpiece velocities in terms of hundred meter per second [2].
1.1.2 Contact Operation:

In a contact operation, the energy is released while the energy source, usually an explosive charge, is in intimate contact with the workpiece. Interface pressure acting on the surface of the material may be several million pounds per square inch, with associated working times measured in microseconds. Pressures are directly related to the material-explosive combination and to the geometry of the material-explosive system. In most contact operations, high
intensity, transient shock waves are induced in the workpiece. These shock waves then propagate through the material, and displace, deform and possibly fracture it.

Explosive forming was one of the most widely used high rate forming techniques. This process was mostly used to form large and bulky components typically for military applications, since conventional presses large enough to form such components were generally not available. Jet Engine shroud was manufactured by Ryan Aeronautical Company by explosive forming [3]. Rohr Corp. used this process to make gas turbine shroud, which involved a combination of stretch and draw forming [2]. Very big and intricate components for the aircraft industry were also made by this process, such as those by Rocketdyne division of North American Aviation Inc. [2]. Explosive forming allowed manufacture of many unique tubular shapes by beading and bulging the work piece in selected areas. Sound suppresser tubes and thrust reverser for Boeing 707 involved bulging of banana tubes, which required high energy that could be delivered only by explosive forming [2]. Martin-Denver produced one piece shells for large propellant tanks using explosive forming. An automobile plant in the erstwhile German Democratic Republic started making rear axle housings using explosive forming in 1981, with 50% investment cost saving and a 10% material saving compared to alternative conventional method [4]. ICI Americas Inc. specialized in using this process for tube plugging, tube expansion and replacement of tube ends [4]. Explosive Fabricators Inc. specialized in making composite tubes, nozzles and other space age components [4]. In addition to these, explosive forming has also been used in
forming components from welded preforms [4]. Such preforms are necessary when the initial tube size is larger than that obtainable commercially or when a specialized starting shape is needed.

1.2 Gas mixture forming:
Gas mixture forming employs energy released by the chemical reaction of a fuel with an oxidizer. The energy may be transferred to the workpiece, through a medium, or through a mechanical device such as a press. Since gas mixture forming is normally performed in an enclosed container, it requires more extensive tooling and greater safety consideration in tool design than the explosive forming. However, it is particularly suitable for rapid cycling and forming of small tubular parts, complex shapes and large thin sections. Peak pressures of 8 MPa have been reported in the literature [5].

1.3 High voltage discharge forming:
Electrohydraulic forming and electromagnetic forming techniques involve storage of electrical energy in capacitor banks and quick discharge over a few microseconds. Hence they are classified under high voltage discharge techniques. Very high pressure is created over a very short period of time which can be used to deform work piece. There are no intermediate machines or devices, such as motors or pumps, to create such pressures. The transient high pressure is developed purely by electrical forces or shock waves.
1.3.1 Electromagnetic forming:

Electromagnetic forming, in its most usual form, uses a capacitor bank, a forming coil and an electrically conductive workpiece (Figure 1.2). A very intense magnetic field is produced by the discharge of a capacitor bank into a forming coil within a few microseconds. This magnetic field induces a current in the work piece in such a direction that it opposes the change that produced it (as shown in Figure 1.2). Two conductors with opposite currents repel each other with the Lorentz repulsion force which results in compression of tubular work piece. By placing the coil inside of the tubular work piece tensile forces can be created to expand the tube.

Electromagnetic forming has been recognized to be highly repeatable. The operation requires only a signal to activate the charging and firing of the capacitor bank, so the current in the coil and the resulting variables: the magnetic pressure, the velocity and radial displacement of the workpiece can be controlled by varying the discharge energy. Peak magnetic pressures are as high as 300 MPa leading to workpiece velocities up to 300 m/s [4] and strain rates up to $10^4$ s$^{-1}$. When compared with explosive forming, the energy released in electromagnetic forming is usually smaller [6,7], thus this forming technique is widely employed for smaller workpieces and thin sections.

Electromagnetic forming is chiefly used to expand, compress or form tubular shapes. It is occasionally used to form flat sheet and it is often used to combine several forming and assembly operations into a single step. The forming operation involves no mechanical contact between workpiece and forming coil. Hence no lubrication is required, nor any post-operation
cleaning. Materials with the specially prepared surfaces can be formed without affecting surface conditions. Finishes can be applied before parts are formed or assembled to other elements. The electromagnetic forming process is not limited in speed by the mechanical inertia of moving parts. The machine can be operated up to 600 - 1200 operations per hour, but the fully automated equipment can reach even higher repetition rates, up to 200 operations per minute [8].

![Diagram of electromagnetic forming process](image)

**Figure 1.2:** Schematic representation of electromagnetic forming  
(Adapted from Ref. 1)
General Dynamics - Convair division was using this process for tube expansion and swaging [3]. General Atomic division of General Dynamics used this process to assemble and form missile components, seal radioactive fuel containers, fabricate drive shaft assemblies, band projectiles and even form irrigation pipes [7]. The principle of electromagnetic forming was also used to develop various other processes. Coining, dimpling and blanking on semi-finished parts without surface damage etc. were reported by Noland [2]. Fine details could be produced in embossing process due to high forming velocities. Cenanovic [9] reported a variation of this process in which the reversed currents and magnetic forces were used to remove the pressure tubes from the fuel channels in CANDU nuclear reactors in Canada. NASA's Marshall Space Flight Center and Advanced Kinetics Inc. developed what was called "Magnelok process" to swage initially aluminum sleeves and later extended to a variety of materials and fastening operations [2]. NASA also used Electromagnetic forming to manufacture large hardware associated with the Saturn booster. Use of high field coils to work as a hammer on conductive work piece was also used for correcting deformation in fuel tanks [2,4]. Boeing used this principle to remove dents in 727 rudder of Aluminum honey comb construction and transportation damage in 727 engine cowling [4]. Diversico Industries, Minneapolis, MN was until recently using electromagnetic forming to shrink locking rings around tube assemblies for critical applications and to swage 99% pure nickel pitot tube using a driver, for the Lockheed SR-71 Blackbird reconnaissance plane [10]. The company developed its own variations of this process and is making over 400 components for fluted proton beam guide tubes for particle accelerator applications in FermiLab, IL [10].
The main restriction of electromagnetic forming is that it can be applied only to good conductors such as copper, aluminum and low-carbon steels. Low conductivity materials can be formed by using the high conductivity "drivers", such as aluminum or copper sleeve. Orava [11] suggested that direct forming is most efficient for materials with conductivity in excess of 0.17 \( \text{\mu mho/in.} \) The expansion of the workpiece can also be limited by joule heating which occurs due to very high induced currents (about 30 kA to 40 kA) in the workpiece.

1.3.2 Electrohydraulic forming:
In electrohydraulic forming, a transient high pressure is created in a liquid, usually water, by means of an electrical discharge across a spark gap. This is achieved by storing electrical energy in a capacitor, or a bank of capacitors, and releasing it suddenly through a pair of electrodes, or to vaporize and explode a wire bridging an electrode gap. The high transient pressure can be used to force metal into a die or mold. Thereafter, the events leading to workpiece displacement are similar to those in explosive forming.

Electrohydraulic effect dates back as early as 1815. Svedberg [12] produced colloidal metal suspensions by means of a capacitor discharge through a liquid. Nagaoka and Futagami [12] reported violent mechanical reactions from capacitor discharges under water. Tracing thus the origin of electrohydraulic forming, Felts [12] observed that Yutkin was the first to recognize that the high transient pressures generated by electrical discharge provide a new, versatile and valuable tool for industrial application. In the
1950s and 1960s, electrical discharge techniques received increasing attention as an alternative to the use of explosives.

The electrode configuration can be engineered in many ways to utilize the shock wave appropriate to the type of components formed as shown in Figure 1.3. A point source creates spherical pressure pulse. Such a spherical pulse is effective in a confined volume, but is inefficient when forming from flat work surfaces. On a flat work piece, only half of the energy from a spherical pulse is utilized. Tubular parts can be formed with almost 100% utilization of cylindrically shaped pressure pulse.

Cylindrical pulse can be generated using two electrodes which can be aligned along a common axis or parallel to one another. The former is called co-axial configuration as shown in Figure 1.4. The latter is called parallel configuration and is shown in Figure 1.5. In co-axial electrode configuration, the pressure pulse travels perpendicular to the electrode axis. Surface erosion or distortion due to shock waves are minimal and so they last longer than the parallel electrodes. They eventually fail due to deformation of outer electrode by the shock waves and subsequent break up of insulation between the outer and inner members.
Figure 1.3: Pressure pulse propagation for various electrodes configuration (Adapted from Ref. 2).
Figure 1.4: Schematic representation of electrohydraulic forming with co-axial electrodes set up for tube bulging (Adapted from Ref.1).

Parallel electrodes can be easily replaced and permit easy variation of stand-off distance and spark gap. The shock waves generated travel parallel to the electrode axis. They have poor life due to distortion by shock wave and magnetic repulsion. Advanced designs employ shock reflectors for greater process efficiency.
Numerous investigations [1,13-20] indicated that important variables that affect this process are the configuration of electrodes, spark gap, bridge wire, stand-off distance (distance between spark gap and workpiece) and discharge energy. Kirk [18] observed that immersed portions of the electrodes under water must be sheathed with polythene tubing, else considerable dissipation occurred at several places along the electrode surfaces. The shape of the electrode tips was found to have little effect on the forming [18]. Kirk also summarized that the effect of medium on forming characteristics was weak. Though methylene chloride was found to be the best medium, water was commonly used due to simplicity [21]. The bridge wire should have high
resistivity and low enthalpy of vaporization. Kegg and Kalpakcioglu [14] investigated aluminum, copper and nichrome wires and found no appreciable difference in performance. Caggiano et al. [21] carried out a detailed set of experiments on various parameters and they prescribed the use of aluminum or magnesium wires for best performance. Sabroff [22] ranked tungsten wire to be the best followed in order by molybdenum, titanium, nickel and aluminum. Finite time will be required to vaporize the wire and this time will increase with increasing wire diameter. If the diameter of the wire increases to over 2.54 mm, the current will flow and energy will be lost in the external circuit. Hodgson [17] reported that use of thin gage copper had practically no effect on the deformation produced. Sufficiently thin wires are not expected to take up much of the available discharge energy. They only make the process easier to control. Noland [23] reported that the melting time of the wire and the pressure build up are similar in the spark type system, where only liquid separates the electrodes. Here, ionized liquid instead of the wire forms the arc channel. Tobe et al. [15] conducted a series of experiments and proposed empirical relations for optimum diameter and length of bridge wire for given values of charging voltage, capacitance and natural frequency of the circuit. By this optimization, they reported that about 80% of the charging energy could be converted to useful discharge. Smaller stand-off distance produces stronger shock, while larger distances spread the force over greater area.

Expensive and intricate coil designs involved in electromagnetic forming are avoided in this method. Circuit inductance must be held to the minimum. Higher circuit inductance increases the time span of energy discharge, thus
undermining the process efficiency. This requirement is more stringent in electromagnetic forming, since the forming coil also adds to the circuit inductance.

Unlike electromagnetic forming, electrohydraulic forming is not suited for radial compression or swaging operations because the energy source is usually a point or a line. However, this itself could be its greatest advantage too. Its capability to localize the energy release provides small scale liquid punch. This provides a means to shape complicated configurations. A wide variety of small parts have been formed by electrohydraulic forming. Electrohydraulic methods are not limited to forming materials which are relatively good electrical conductors.

The electrohydraulic forming is suited for sheet metal forming and the explosive forming is more suited for bulk forming. Advantages of electromagnetic and electrohydraulic forming over explosive forming are, more economical multi-part capability, substantially lower noise level and less hazardous operation.

General Dynamics - Convair division was using electrohydraulic forming for simultaneous blanking and forming [3]. General Electric was using this process to make missile components out of aluminum, using 360 μF capacitors and up to 10 kV voltage [24]. Vickers Limited, Newcastle used banks up to 40 kJ to produce various parts such as a swivel joint out of stainless steel, combined piercing and forming on thin aluminum sheets, assembly of components using various Al alloys, copper alloys, Nimonic 75
Division in which forming problems were successfully eliminated with the
use of electrohydraulic forming on copper, 6061 T0 Al and stainless steel.

Figure 1.6: ElectroshapE Electrohydraulic forming unit with discharge
energy capacity of 25 kJ (l).

Cincinnati Shaper Co. was manufacturing Electrohydraulic forming
machines under the trade name of "Electroshape", in capacities of 25 to 150 kJ.
One such machine is shown in Figure 1.6. Rohr Corp. was producing a
machine under another trade name "Soniform" in 15 to 60 kJ range. More
details about these two processes are available elsewhere [2]. Diversico
Industries, Minneapolis, MN was using electrohydraulic forming to make 762 mm long stainless steel exhaust nozzle for jet engines and deicer tubes for McDonnell Douglas DC-9-80 jetliner [10]. The company has reportedly benefited also from low technology spin-off from this technology on a variety of other applications.

1.4 Pneumatic-mechanical forming:

![Diagram showing pneumatic-mechanical process](image)

**Figure 1.7: Principle of pneumatic-mechanical process**
These are essentially presses capable of a ram or piston speed of up to about 30 m/s, approximately an order of magnitude faster than conventional presses. The high speed is obtained by the use of a compressed gas, air or nitrogen, and with the aid of a seal which permits rapid punch loading.

The principle of this seal, as shown in Figure 1.7, is to have gas at a pressure $p_1$ acting over the upper surface area $A_1$ of a piston, whilst on the lower surface of area $A_2$, a pressure $p_2$ acts. The seal is maintained as long as $A_1p_1 > A_2p_2$. A small imbalance, in which $A_2p_2$ is caused to exceed $A_1p_1$, results in the seal breaking and higher pressure $p_2$ acting the whole of the lower face, so that the piston or ram thereupon accelerates. Thus, some of the expansive energy of the gas is converted into kinetic energy of the ram which is dissipated by doing plastic work on the workpiece.

1.5 Pneumatic-hydraulic forming:
In this process, the energy source itself is compressed air which, on expansion, drives a mechanical piston or plunger into a contained fluid (commonly water). The fluid is then compressed, which in turn transfers the hydraulic pressure to the workpiece. Forming velocities are similar to those achieved in any high rate processes and hydraulic pressures are up to 700 MPa. This is reported to have been originally developed by the Japanese, who called it "Hydropunch" [26].

Examples of typical application for high speed presses include extrusion of 6061 Aluminum by Western Gear Corporation and forging of 9310 steel by Bendix Corporation [12]. Electrodynamics Division of General Dynamics
manufactured these presses under trade name "Dynapak", which was originally developed by the company's Convair Division. Precision Forge Co., Santa Monica, CA was making these machines with a maximum speed of 20 m/s in 1980s [4]. Other makers of this equipment include Production Machine division of U. S. Industries, Fairchild Metal Products division of Fairchild Camera and Instrument Corp. The latter termed their press CEFF (Controlled Energy Flow Forming) [2]. These presses appear to have been used more to do forging and blanking operations than forming as such. Petroforge is another high speed press developed by University of Birmingham, which eliminated the use of hydraulics and had a maximum velocity of 20 m/s [4].

1.6: Benefits of high velocity forming

High rate processes were commonly known to possess the following advantages which made them unique.

1. Energy is transferred from equipment to work piece mostly as kinetic energy by impact unlike in conventional processes where energy transferred is mostly pressure energy [1].

2. Large integral parts could be produced with little tooling. Only one sided dies are required [21].

3. Difficult-to-form materials could be formed more readily. In some cases components could be fabricated which could not be otherwise formed by any other process. Complex shapes are possible [4].

4. Surface blemishes were minimized due to the absence of a male punch [1].
5. A wide variety of materials could be formed [27].

6. All high rate processes could reproduce surface details very well, which could not be achieved by conventional pressing methods [1].

7. Spring back in components produced was minimal [1].

8. Forming and assembly could be combined into one operation. This also facilitated easy assembly of even dissimilar materials [2].

In summary, high velocity forming is the shaping of materials by quickly conveying energy to them during short durations. High speed material movement is rapidly acquired so that kinetic energy is quickly acquired by the workpiece and, by virtue of the prescribed peripheral restraints, is dissipated as plastic work in achieving the desired plastic deformation. Since large part of the imparted energy to the workpiece is in the form of kinetic energy, the nature of deformation and metallurgical phenomena are not the same as one would see in conventional processes. While many of the unique features of high rate processes are well documented, reasons for such uniqueness appear to be not well understood. Clear understanding of these phenomena would no doubt help utilize these processes to their fullest potential and may open up possibilities of forming those materials which are currently difficult to form by other means.
CHAPTER II

LITERATURE REVIEW

2.1 Explosions and shock propagation in water:

Most of the studies on explosions and shock propagation in fluids involved water as a medium, since it was the simplest one to study. Also, due to its potential significance to Naval Research, water played an important role in these studies.

One question that naturally arises is what are the changes that occur in the property of water when shock waves are generated and propagated through it. Water is considered to be incompressible under normal conditions, since disturbances affecting it are slowly changing and water can accommodate itself to them before the disturbance has changed appreciably. Under such conditions, the disturbance spreads instantaneously to all points in the liquid. Motion which can be accounted this way is usually described as incompressible flow.

In the regions of water surrounding an explosion, pressures are very large. If we can restrict ourselves to the concept of water as a homogeneous fluid incapable of supporting shearing stresses, we have a medium in which the
volume can readjust itself to the displacements of its boundaries by flow. In addition, changes in pressure on a definite mass leads to changes in volume (compression) of the mass. So when shock waves are generated in it, water behaves like a compressible medium. Thus, pressure applied at a localized region in the liquid will be transmitted as a wave disturbance to other points in the liquid. The wave involves local motion of the water and changes in pressure.

Explosions take place not only in manufacturing processes like explosive forming and electrohydraulic forming, but also in war situations and in submarines. Hence, there has been a lot of research done in the defense laboratories. Thus, there are some useful summaries and reviews available which can be of use in designing a high velocity manufacturing system. Many such studies involved explosives and so are directly relevant to explosive forming. With the help of some work done in directly relating this to electrohydraulic forming, such concepts appear to be useful to electrohydraulic forming too.

While studying the generation and propagation of shock waves [28], the quantities that are of interest are the pressure, density and particle velocity behind the shock front in terms of the corresponding quantities ahead of it. Also of interest are velocity of the front, pressure-time profile and pressure-distance profile. With events occurring in a few nano seconds, measurement of these parameters is very difficult and many times inaccurate. Hence, empirical relations and some simplified analytical expressions are frequently used in conjunction with limited experimental measurements in order to
understand the physical phenomena taking place [5]. A gram of typical explosive has been consistently observed to release 4 to 5 kJ of energy. In the case of electrohydraulic forming, stored energy in the capacitor banks is given by (1/2) CV², where C is the capacitance of the capacitor bank and V is the charging potential. However, estimates of how much of this energy is converted to useful mechanical energy vary widely from 2% to 50%.

2.1.1 Detonation:
The process of detonation is a detailed analysis of events since an explosive begins producing large amounts of energy until the whole chemical reaction is complete. This too involves generation of shock front during start of chemical reaction and propagation of the shock front till the explosion is complete, much like how the shock wave propagates subsequently in water till it hits a workpiece to do useful plastic work. However, these shock waves propagate within the volume of explosive and has many other distinguishing features from the latter shock wave, hence the terms detonation wave, detonation front and detonation velocity are used to refer to such quantities. Predictability and consistency are reported to be much better in the case of detonation. Once the chemical reaction is started, detonation wave is generated. Continued chemical reaction supplies chemical energy which ensures a continuous supply of energy behind the detonation wave. This is in contrast to the nature of shock wave generated by the explosion in the water. The latter continuously tapers off in strength since the time it is generated.
Analytical solution to detonation wave equations require determination of Pressure (P), density (ρ), particle velocity (u) and detonation velocity (D). The density of the explosion products increases typically 30% over the initial density of the explosive. Particle velocity is the velocity of a point moving with the wave. It is typically of the order of 1500 m/s in explosive forming operations. Detonation velocity is the sum of the particle velocity and the sound speed in the burned gas. In physical terms, it means that the detonation front moves at the sound velocity with respect to the gas behind it. Three equations are provided by the laws of conservation of mass, momentum and energy. In order to solve for all the four unknowns, the necessary fourth equation is provided by various empirical rules. One such rule that is frequently encountered in shock forming literature is Jouget empirical rule [28]:

\[ D = c + u \]  

(2.1)

where c is velocity of small amplitude waves in reaction products behind the shock front. The detonation velocity varies typically from 2000 m/s to 8500 m/s depending upon the type of explosive used. It is reportedly well known for standard explosives. The products of detonation are usually confined to original volume of solid or liquid. From gas laws and laws of thermodynamics, the temperature of the products of detonation can also be determined:

\[ \frac{1}{2} \frac{n}{\gamma} \frac{R}{\gamma} \frac{T}{T_0} = Q + \frac{C_v}{T} (T - T_0) \]  

(2.2)
where $Q$ is the heat input into the reaction and $\gamma$ is ratio of specific heats. The products are typically at a temperature of $3000^\circ K$ to $5000^\circ K$ and at a pressure of over 5000 MPa [28]. If the detonation pressure for an explosive is not known, it can be approximately calculated as follows [29]:

$$P_x = \frac{\rho_x D_x^2}{4}$$  \hspace{1cm} (2.3)

Thickness of detonation front is estimated to be about a few microns. So in a few nano seconds, the detonation shock covers the distance of its front thickness. Since reaction equilibrium calculations have been verified experimentally to be accurate, it follows that the reaction completes within a few nano seconds, before the shock front conditions change. Cole [28] showed that detonation wave forms also can be analytically determined.

### 2.1.2 Events following detonation:

Description of the sequence of operations following detonation process was given by Wilson [5]. Detonation produces a high intensity spherical bubble which expands to a maximum radius. This bubble goes through an oscillatory motion until it vents at the surface. With each oscillation, the energy is released to the surrounding water. As a result, the bubble alternately shrinks and expands in radius and tries to release its remaining energy to the atmosphere producing a water plume. However, the author did not offer any experimental evidence to support such a mechanism. Estimates of energy partition in the process [28] shows that the pressure pulse accounted for about 60% of the available energy, the first oscillation for about 25% and the remaining behavior of the bubble for the other 15%. The maximum
bubble radius occurs during the first period and is empirically given by Wilson [5] as,

\[ r_m = J \left( \frac{W}{d + 33} \right)^{1/3} \]  

(2.4)

where \( r_m \) is radius in feet, \( W \) is the weight of the charge in pounds, and \( d \) is the depth in feet to which the charge is submerged. \( J \) is the explosive constant which is well known for standard explosives. A similar expression for determining the period of first oscillation is given by Wilson [5],

\[ T = K \frac{W^{1/3}}{(d + 33)^{5/6}} \]  

(2.5)

where \( T \) is the bubble period in seconds and \( K \) is a constant specific to explosive and is known. As an example, a 0.454 kg (1 lb) charge of TNT detonated 1.067 m (15 ft.) below the surface will produce a bubble with a maximum radius of about 1.067 m (3.5 ft.) and a period of about 173 milli seconds for the first oscillation. Design of explosive processes is done in such a way that the bubble breaks over the work piece in its first oscillation.

Orava and Wittman [11] described the process of effect of shock waves generated in under-water explosions, on sheet metals. Though the explanation was provided for stand-off explosive forming, the events that occur in electrohydraulic forming are similar.
Figure 2.1: The effect of shock wave on a typical sheet sample (adapted from Ref. 11).

The shock wave interactions with sheet sample are illustrated in Figure 2.1. The incident shock pressure pulse (1) accounts for nearly 60% of the explosive energy. This is partially reflected at the front face of the workpiece (2) and partially transmitted into the workpiece (3). The acoustic impedance of the workpiece material is much higher than that of the water; it is about 25 times in the case of steel. Hence the compressive stress associated with the transmitted wave is nearly double that of the incident pressure. Due to conservation of momentum, this imparts a particle velocity up, to the workpiece. At the back of the workpiece, the transmitted wave is reflected.
almost completely as a rarefaction wave (5), due to negligible impedance of
air. Thus the transmitted part (4) is very small. As a result of this reflection,
the particle velocity almost doubles. The tensile wave (5) is again reflected at
the nearly free water/workpiece interface, but as a compressive wave (7) of
lower magnitude than (5), thus increasing the particle velocity to almost 3 \text{ up}.
This ringing effect will continue until the wave attenuates completely due to
deformation and other losses. Thus each successive reflection contributes to
the forming process but in decreasing amounts. Orava and Wittman [11]
offered no detailed analysis nor any experimental data to confirm these
processes, but acknowledged that the explanation was over-simplified.
Notably, the lateral wave components were neglected and wave interactions
were also neglected.

In Electrohydraulic forming, processes that occur after the stored electrical
ergy is discharged into the spark gap, or to the wire to be exploded, can be
analyzed in a fashion similar to that in explosive forming. Such an analysis
was provided by General Dynamics [13]. The current of a few thousand
amperes will heat a typical wire (1 mm diameter Aluminum) to almost
5500\degree \text{C} in 0.1 \text{ µs}. Inertial forces, assisted at first by magnetic fields, contain the
material. The pressure on the wire's axis increases to many thousands of
atmospheres. This leads to explosive expansion. At the beginning of the
expansion, the material becomes non-conducting compressed gas and the
current is interrupted. The expanding metallic vapor pushes a shock before
it. In a few micro seconds, the gas has thinned out sufficiently to permit the
initiation of a normal gas discharge. The arc channel continues to expand
until all the electrical energy is drained from the circuit or when the arc
channel becomes highly resistive and extinguishes the circuit due to energy losses [12]. To give an idea as to how fast these processes occur, at 10 ns, enough energy is put into the wire to melt it completely. At 12 ns, the wire begins to vaporize at one atmosphere and, at 17 ns, enough energy has been developed to completely vaporize it. Pressures of about 241 MPa is reported to have developed at a distance of 25 mm from an aluminum wire of 1 mm diameter for a discharge from 18 kJ (1800 μF - 4500 V) energy source [13].

2.1.3 Shock wave propagation:

Analytical solution to wave forms in under water shock propagation involves determination of the same four parameters Pressure (P), density (ρ), particle velocity (u) and velocity of the front as for the detonation waves. Once again, three equations are provided by the laws of conservation of mass, momentum and energy. Various theories have been put forth to provide the fourth necessary equation. Help is also taken from the principle of similarity which can be stated as follows:

If the linear size of the charge be changed by a factor k, the pressure conditions will be unchanged if new distance and time scales k times as large as the original ones are used. As an example, the pressure and duration of shock wave at 10 m from a charge of size 10 mm x 10 mm x 10 mm at time t will be the same as for a charge of size 20 mm x 20 mm x 20 mm at a distance 2 x 10 m in time 2 x t.

That is, Pressure is a function of density only and depends on equation of state and $C_V$. Hence, specific solutions of the form $P(r,t)$ and $u(r,t)$ are possible.
for the wave form, where \( r \) is the vector distance from an arbitrary origin [26].

In order to solve the wave forms, theories make use of thermodynamic properties of shock wave propagation. One example is Tait equation [28]:

\[
V(T,P) = V(T,0) \left\{ 1 - \frac{1}{n} \log\left(1 + \frac{P}{B}\right) \right\} 
\]

(2.6)

or

\[
\left( \frac{\partial V}{\partial P} \right)_T = \frac{1}{n \left[ P + B(T) \right]} 
\]

(2.7)

where \( n \) is a constant and \( B \) is a function of temperature only. Theories also made use of Riemann's treatment, which is based on introducing a new variable \( \sigma \) defined by,

\[
\sigma = \int_{\rho_0}^{\rho} c(\rho) \frac{dp}{\rho} 
\]

(2.8)

where \( \rho_0 \) is the initial density in the absence of a disturbance and the sound velocity \( c \) is a function of density as shown in equation 2.9.

\[
c = \sqrt{dP/d\rho} 
\]

(2.9)

Major theories of shock wave propagation in fluids [28] are by (1) Penney and Dasgupta, (2) Kirkwood and Bethe and (3) by Kirkwood and Brinkley. Penney and Dasgupta used Riemann equation and predicted wave profiles. Kirkwood-Bethe theory assumed that change in entropy behind the shock front was zero. They also introduced a new variable called enthalpy of fluid, \( H = E + P/\rho \). This theory seems to have received the best acceptance by
researchers working in the field of shock dynamics. Kirkwood-Brinkley theory enabled development of equations so that solutions obtained for single distance could be extended to other distances. Comparison of these theories to the experimental observations is shown in Figure 2.2. It is not clear whether this comparison was done at an assumed time or in an assumed medium.

![Figure 2.2: Comparison of shock theories with experimental observations (Data from Ref. 28)](image)

### 2.1.4 Some empirical rules used in high velocity forming:

A typical pressure pulse generated by under water explosion will have a pressure-time profile as shown in Figure 2.3. It can be approximated by the expression

\[ P = P_m e^{-t/\theta} \]  \hspace{1cm} (2.10)
where \( P \) is the pressure as a function of time, \( P_m \) is the peak pressure at that distance, \( t \) is time after the arrival of the pressure front and \( \theta \) is the time it takes for the pressure to fall to \( 1/e \) of its peak value. This approximation is justified by the argument that most of the useful work is accomplished by the shock wave by the time the pressure drops to \( 1/e \) of the peak value.

By fitting the available extensive experimental data, additional empirical expressions have been formulated [5]:

\[
P_m = A \left( \frac{W^{1/3}}{R} \right)^\alpha \tag{2.11}
\]

\[
I = B \ W^{1/3} \left( \frac{W^{1/3}}{R} \right)^\beta \tag{2.12}
\]

\[
E = C \ W^{1/3} \left( \frac{W^{1/3}}{R} \right)^\gamma \tag{2.13}
\]

\[
\theta = D \ W^{1/3} \left( \frac{W^{1/3}}{R} \right)^\delta \tag{2.14}
\]

where \( P_m \) is the peak pressure in psi, \( I \) is the impulse in lb-sec/in\(^2\), \( E \) is the energy flux passing through a unit area of a fixed surface lying normal to the direction of propagation of the wave in in.-lb/in.\(^2\), \( W \) is the charge weight in pounds and \( R \) is the stand-off distance in feet. The explosive constants \( A, B, C, D, \alpha, \beta, \gamma \) and \( \delta \) are available for standard explosives [5].
Figure 2.3: Typical Pressure-time profile of a shock wave generated by under water explosion (Data from Ref. 5)

Another useful, but somewhat less precise expression for determining peak pressure as a function of charge weight, distance, and explosive type is given by Roth [30]:

\[ P_m = 155 \left( \frac{W^{1/3}}{R^{1.15}} \right) D_x^{1/2} \]  

(2.15)

where \( D_x \) is the detonation velocity of the explosive in feet per second. This is simple and makes use of far more readily available detonation velocity data than \( A \) and \( \alpha \). The impulse \( I \) can be calculated by

\[ I = \int_0^t P(t) \, dt \]  

(2.16)
From experience, it has been found that integration up to five times $\theta$ gives realistic estimates of impulse [5].

Wood et al. [31] developed weight equivalents of explosives for various capacitor discharge energy levels that would produce the equivalent shock waves under water. These are shown in Table 2.1. Since the detonation velocity of any given explosive is known, peak pressures generated in the electrohydraulic forming can be calculated using Roth's equation. For example, in the sheet metal forming experiments of Tobe et al. [15], the discharge energy was 0.85 kJ and the standoff distance was 100 mm. If TNT is taken as an equivalent explosive for our calculations, the corresponding weight of explosive from Table 2.1 for a capacitor discharge energy of 0.85 kJ is $4.8535 \times 10^{-4}$ lbs. The detonation velocity of TNT is 22,600 ft./s [5]. Roth's equation predicts a peak pressure of 6600 psi (45.49 MPa). Tobe et al.'s [15] actual experimental measurement of pressure was 46 MPa. There are also other observations of pressures in electrohydraulic forming. Maccaulay [32] reported pressures of about 1200 MPa for capacitor discharges of 6 to 200 kJ. Noland [2] reported typical pressures of the order of 1000 MPa under typical discharge conditions in electrohydraulic forming. However, these reports did not describe the experimental conditions under which such pressures were observed.

Recently Gourdin [33] demonstrated that the stresses as well as the velocity Vs. time profile for an electromagnetically expanding ring can be readily predicted. Computer codes are also available that allow much more complex two dimensional problems to be solved. CALE is a two dimensional arbitrary
Lagrangian Eulerian code written in the "C" language that includes both Maxwell's equations as well as the equilibrium and compatibility equations that are common in metal forming simulation codes [34]. Recent comparisons between CALE and simple one-dimensional equations formulated by Gourdin [33] show excellent agreement for situations that can be approximated as being one-dimensional [35].

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Capacitor discharge energy x 10^{-3} Joules</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Mercury Fulminate</td>
<td>27.9</td>
</tr>
<tr>
<td>Lead Azide</td>
<td>32.7</td>
</tr>
<tr>
<td>Diazodimtrophenol</td>
<td>14.7</td>
</tr>
<tr>
<td>Lead Styphinate</td>
<td>32.5</td>
</tr>
<tr>
<td>T.N.T.</td>
<td>13.0</td>
</tr>
<tr>
<td>Tetryl</td>
<td>10.7</td>
</tr>
<tr>
<td>RDX</td>
<td>9.3</td>
</tr>
<tr>
<td>PETN</td>
<td>8.7</td>
</tr>
<tr>
<td>Ammonium Nitrate</td>
<td>34.7</td>
</tr>
<tr>
<td>Nitroglycerin</td>
<td>8.1</td>
</tr>
<tr>
<td>Nitrocellulose</td>
<td>12.4</td>
</tr>
<tr>
<td>Picric acid</td>
<td>12.0</td>
</tr>
<tr>
<td>Nitroguanidine</td>
<td>16.6</td>
</tr>
<tr>
<td>Haleite</td>
<td>9.4</td>
</tr>
<tr>
<td>50-50 Amstol</td>
<td>12.2</td>
</tr>
<tr>
<td>80-20 Tritanol</td>
<td>8.2</td>
</tr>
<tr>
<td>50-50 Pentolite</td>
<td>9.8</td>
</tr>
<tr>
<td>Torpex</td>
<td>8.0</td>
</tr>
<tr>
<td>Tetracene</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Table 2.1: Weight equivalents of explosives in grams for various capacitor discharge energy levels (Data From Ref. 31).
2.2 Observations of improved ductility at high rates:

Many examples can be found in the high rate forming literature on how components requiring severe contours could be successfully formed using a high rate process, which could not be formed by conventional means. However, systematic scientific studies to understand the reasons behind it were very rare. Wood et al. [27] conducted a detailed investigation on formability changes in various high rate processes. Their work encompassed a wide variety of materials and many high rate processes. In free bulging of sheets using explosive forming, six materials showed increase in ductility, while three materials showed a decrease compared to conventional forming. In tube bulging, three out of five materials showed increase in elongation up to as high as 80%, and two materials showed no change. Their experiments on forming with dies produced mixed results. While many materials showed some improvement in formability, 2024-O aluminum and Titanium alloys showed decrease in ductility. Overall, they concluded that seven out of eleven materials tested showed increase in ductility ranging from 4% to 77%. Especially, austenitic, semi-austenitic and martensitic stainless steels, tool steels and nickel base super alloys showed improved ductility at high rates. For some materials tested they also observed lower ductility in electrohydraulic forming compared to explosive forming.

Wood et al. [27] investigated in detail the formability changes at high rates using a variety of high rate forming processes. Figure 2.4 shows the summary of formability data obtained by wood et al. in tensile tests. Figures 2.5 summarizes similar results in tube forming experiments and Figure 2.6 shows their results in dome forming.
When materials were tested under tension, many materials exhibited three zones of formability change in Wood et al.'s [27] work. The uniform elongation increased with velocity first, stayed the same over the next higher range of velocities and decreased sharply after a second critical velocity. The first region was absent for some metals of relatively low ductility. Although the range of velocities for maximum ductility varied from material to
material, all of the materials tested by Wood et al. attained the maximum ductility at 20 m/s.

![Graph of Average Strain vs. Velocity](image)

**Figure 2.5: Average strain Vs. Tube velocity [Data from Ref. 27.]**

Results of tube bulging experiments by Wood et al. [27] are shown in Figure 2.5. None of the five materials tested showed a critical forming velocity beyond which ductility drops rapidly. The 17-7 PH stainless steel, the Rene' 41
and Vascojet 1000 tubes showed an increase in ductility starting at static conditions and extending to the moderate velocity range. Two materials, A-286 stainless steel and Ti-6Al-4V, showed no ductility change over the entire velocity range tested.

Figure 2.6 shows the variation of ductility with forming velocities reported by Wood et al. [27] under approximately biaxial stress condition by using dome bulging tests. Most of the materials in these tests exhibited increased ductility as in uniaxial tension. A critical velocity existed for each of the materials beyond which negligible ductility existed.

From the experimental results of Wood et al. [27], it is clear that for most of the materials studied, an optimum forming velocity range exists for formability improvement. Materials can be classified into three groups based on the ductility of materials under static conditions, optimum velocity range and the extent of formability improvement obtained at high rates.

1. Metals and alloys which have high ductility under static conditions and substantially higher ductility in the optimum velocity range. Of the materials tested by Wood et al., 17-7 PH semi-austenitic stainless steel was the only metal in this class.

2. Metals and alloys with moderate ductility under static conditions and equal or slightly greater ductility in the optimum velocity range. This category includes Vascojet 1000 martensitic tool steel, A-286 austenitic stainless steel, Rene' 41 nickel-base superalloy, Haynes 25 cobalt-base superalloy, 2024-0 aluminum and USS 12 MoV martensitic stainless steel.
Figure 2.6: Average strain Vs. Dome velocity [Data from Ref. 27]
3. Metals and alloys with low ductility under static conditions and equal or slightly greater ductility in the optimum velocity range. This class includes Ti-13V-11Cr-3Al and Ti-6Al-4V alloys.

Caggiano et al. [21] conducted a series of experiments to understand effects of various process parameters in electrohydraulic forming. Some useful observations were also made on material formability. Ti-6Al-4V sheets showed better formability at high rates in annealed condition. In aged condition, formability was better in conventional hydrostatic forming in Ti-6Al-4V and Rene-41 nickel base alloy. Contrary to Wood et al.'s observation [27] on 2024-O aluminum, Caggiano et al. [21] observed increased formability at high rates in electrohydraulic forming. Other materials that showed increase in formability in electrohydraulic forming are 2024-T4 aluminum and 4130 steel in annealed and heat treated conditions. The strain rates employed in this work was of the order of 116 - 994 s\(^{-1}\). Metal velocities ranged from 73 m/s to 175 m/s. High rate forming was accomplished with discharges from a 960 \(\mu\)F capacitor and charging voltage ranging from 4 kV to 15 kV (discharge energies ranging from 7.68 kJ to 108 kJ).

Orava and Wittman [11] attempted to explain the increases in ductility sporadically observed in many of the high rate processes. They observed that instability strain increased at high impact velocity in tensile test. They then sought out plastic wave whose stress amplitude was the same as the dynamic yield stress of the material. The particle velocity corresponding to such a stress wave was found to reasonably agree with the impact velocity at which they first found increase in instability strain. Thus, they attributed increased
ductility to onset of plastic stress wave propagation. Under these conditions, the effective gage length of specimen is reduced substantially, with concomitant rise in strain rate. Strain hardening coefficient has a positive strain-rate sensitivity at such high strain rates. Since strain hardening coefficient controls the maximum uniform strain, the latter undergoes rapid increase at high strain rates. However, a recent analysis [36] suggests that such high rates increase the rate of work hardening and, at a given strain, this gives the appearance of increased rate sensitivity.

Independent of all such research on high rate forming, research in the area of dynamic deformation has also been growing over the years. It has long been felt that if the test velocity is increased in conventional tensile testing, ductility of material used to be lower. However, a few researchers explored ductility at strain rates beyond the conventional capabilities of tensile testing machines and were able to see that ductility increased significantly with increase in strain rate.

Regazzoni and Montheillet [37] carried out tensile tests on Oxygen Free high Conductivity (OFHC) Copper (99.99% Cu) and Tantalum (99.8% Ta) at room temperature over a range of strain rates from $6 \times 10^{-5}$ s$^{-1}$ to $3 \times 10^{3}$ s$^{-1}$. They found that the elongation to fracture of copper remained almost constant at 55% (Figure 2.7) at low strain rates and started increasing at about $10^{3}$ s$^{-1}$ to a value of about 80%. On the other hand they found that Tantalum showed a decrease in tensile ductility over the same strain rate range (Figure 2.8).
Figure 2.7: Dependence of ductility of copper on strain rate (37)

Increases in tensile elongation at high strain rates very similar to what has been observed by Regazzoni and Montheillet on OFHC Copper had also been observed by Meyer et al. [38] on low alloy grade 4330 steel. The strain rate at which the ductility showed rapid increase was again close to $10^3$ s$^{-1}$. However, they did not find any increase in ductility in 18Ni-maraging steel (18%Ni-8%Co-5%Mo-0.6%Ti steel) and austenitic steel (21%Cr-15%Ni-7%Mn-3%Mo steel) even up to strain rates of $10^4$ s$^{-1}$. They used servo-hydraulic testing machine for low strain rates, pendulum impact for intermediate strain rates and flywheel for high strain rate tensile testing.
Figure 2.8: Dependence of ductility of Tantalum on strain rate (37)

Tensile tests done on X45 Cr Si9 3 steel by Meyer [39] over seven orders of magnitudes of strain rates showed (as in Figure 2.9) decreasing total elongation with strain rate and a sudden rapid increase at a strain rate of $5 \times 10^3$ s$^{-1}$. Once again the techniques used to achieve various strain rates were servo-hydraulic testing machine for low strain rates, pendulum impact for intermediate strain rates and flywheel for high strain rate tensile testing.
Figure 2.9: Stress-Strain behavior of quenched and tempered X45CrSi9 3 steel at various strain rates (39)

Olive et al. [40] studied rupture behavior of some metals in explosive expansion. Explosive shocks of about 50 GPa generated high stresses and strain rates of the order of $10^3 - 10^5$ s$^{-1}$ on the tested materials. Tests involved spherical and radial expansion on materials such as aluminum alloy, zirconium alloy, three uranium alloys, various steels, a titanium alloy, a nickel alloy, an austenitic iron alloy and a cobalt alloy. They reported that
rupture occurred at very high strains compared with those in static or
dynamic tests. Winter [41] studied similar fracture behavior by radially
expanding a metal cylinder. He used small gas gun to fire a nylon projectile
to expand a silastomer rubber, which in turn expanded cylindrical metal
specimen located around it. With surface grid markings and with the help of
high speed photography, fracture strains were measured. He reported sharp
increases in failure strain in mild steel, naval brass, phosphor bronze and
moderate increase in copper over a strain rate range of about $1 \times 10^4 \text{s}^{-1}$ to $3.5 \times
10^4 \text{s}^{-1}$.

Kobayashi et al. [42] studied differences in tensile fracture elongation of five
Al-Li alloys, pure Aluminum and aluminum alloys of grades 2024 and 7075.
Quasi-static tensile test was done at $10^{-3} \text{s}^{-1}$. High strain rate tensile tests were
done at a strain rate of $10^3 \text{s}^{-1}$ using a rotating disk type high velocity tensile
tester. They found very significant increases in ductility (up to about 150%
increase over those at conventional static strain rates) on all the materials
except 7075 Al alloy.

The report of improved ductility at high rates in the high rate forming
literature can be summarized as shown in Tables 2.2 and 2.3. Reported
improvements in tensile elongation is summarized in Table 2.2. Detailed
analyses of biaxial formability improvements at high rates are summarized in
Table 2.3.
<table>
<thead>
<tr>
<th>Material</th>
<th>Improvement</th>
<th>Strain rate (s(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Elongation increased from 0.55 to 0.80</td>
<td>(10^3)</td>
<td>37</td>
</tr>
<tr>
<td>4330 Steel</td>
<td>Minor improvement</td>
<td>(10^3)</td>
<td>38</td>
</tr>
<tr>
<td>18 Ni Maraging steel &amp; Austenitic steel</td>
<td>None</td>
<td>up to (10^3)</td>
<td>38</td>
</tr>
<tr>
<td>X45CrSi9 3 steel</td>
<td>Elongation increased from 0.23 to 0.34</td>
<td>(5 \times 10^3)</td>
<td>39</td>
</tr>
<tr>
<td>Various</td>
<td>Higher fracture strains</td>
<td>(10^3) to (10^5)</td>
<td>40</td>
</tr>
<tr>
<td>Various</td>
<td>Sharp increases</td>
<td>(10^4)</td>
<td>41</td>
</tr>
<tr>
<td>Various Al alloys</td>
<td>150% increase</td>
<td>(10^3)</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 2.2: Summary of increased elongation observed at high strain rates in tensile test.

<table>
<thead>
<tr>
<th>Material</th>
<th>Improvement</th>
<th>Strain rate (s(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Various (7 materials)</td>
<td>Increase up to 80%</td>
<td>Various high rate processes</td>
<td>27</td>
</tr>
<tr>
<td>2024 - O Al and 4 Titanium alloys</td>
<td>Decreased formability</td>
<td>Various high rate processes</td>
<td>27</td>
</tr>
<tr>
<td>2024 - T4 and &quot;O&quot; Al and 4130 Steel</td>
<td>Increase</td>
<td>Electrohydraulic (116-994 s(^{-1}) (73 - 175 m/s)</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 2.3: Summary of increased biaxial formability at high strain rates.
2.3 Flow stress measurements at high rates:

Flow stress measurements done on OFHC Copper by Follansbee, Regazzoni and Kocks [43] showed a rapid increase near a strain rate of about $10^3$ s$^{-1}$. Meyer et al. [38] had also found that UTS and yield strength varied in the similar fashion for the 4330 steel in which increased elongation was observed at high strain rates. On the other two steels in which they did not observe increased ductility at high strain rates, the changes in UTS and yield strength were monotonic and continuous increase with strain rate with no noticeable abrupt changes in the high strain rate region.

![Graph showing variation of yield strength and ultimate tensile strength](image)

Figure 2.10: Variation of yield strength and ultimate tensile strength of quenched and tempered X45CrSi9 3 steel (Data from Ref. 39).
In a later work by Meyer [39] ductility of steel showed a rapid increase abruptly at a strain rate of $5 \times 10^3 \text{s}^{-1}$, but according to the author, the UTS and yield strength showed not-so-abrupt change near such high strain rates. While the change is not as dramatic as seen in other cases, there is indeed a significant change in UTS and yield strength data at room temperature as seen in Figure 2.10.

Orava [11] summarized changes in other properties of materials when deformed in high rate processes as compared to conventionally processed components. This appears to be the only available summary on these aspects. Charpy impact strength and Ductile-Brittle Transition Temperature of explosively formed 4130 steel was better than cold rolled part in the longitudinal direction, but worse in transverse direction. Grade 4340 steel had these properties equivalent or better than cold rolled part in both longitudinal and transverse directions. Fatigue resistance is believed to be the same or better when components are formed at high rates. However, there appears to be no systematic study reported on this aspect. Stress rupture life of shock deformed 304 stainless steel reportedly increased by over an order of magnitude and the minimum creep rate reduced by three orders of magnitude. Stress corrosion resistance of Ti-6Al-4V is reportedly unaffected by the forming rate, but austenitic stainless steel showed decreased resistance. There are also reports that this may be due to cold worked condition of the material and fully annealed materials showed higher stress corrosion resistance no matter what the forming velocity was. After some detailed microstructural analysis of components formed at high rates and low rates, Orava [11] concluded that the microstructural changes which are introduced
by high rate processes have much the same influence on terminal properties and thermal response as conventional metal working, with some notable exceptions.

2.4 Significance of improved formability to industry:
Demands on increased formability on various sheet metals used in a variety of applications come from various sources. For example, in the automotive industry, weight reduction efforts drive substitution of steel with higher strength thin steel sheets or with totally different light weight materials like aluminum. In such situations, formability is no doubt an important issue. Superplastic forming is currently a solution to such formability problems. But, it requires use of specially processed materials. This increases material cost so much that final benefits are reduced or even outweighed. Also, superplastic forming involves forming at high temperature and are required to be done at such low rates where productivity is seriously undermined.

In contrast to the above situation, if it can be shown that formability improves in high rate forming processes, most of the above limitations can be avoided. Sporadic observations in literature suggest such a possibility, though this aspect has not been studied seriously enough. Capital cost required may be significant compared to superplastic forming, but with judicious application, this can be justified. Commercial availability of capacitor banks and use of electromagnetic forming already in the industry promises quick exploitation of this technique in solving formability related issues. Since manufacturing cost is increasingly becoming a major consideration, other well known advantages of high rate processes can be
taken advantage of, such as their ability to combine forming and assembly, reduced tooling cost (only a female die is required) and reduction in number of operations performed to produce a component.

2.5 Possibilities of improving biaxial formability:
Understanding the true mechanism behind improved formability in a high velocity forming process is very important in order to commercially utilize these benefits in actual application. Consider a typical engineering stress-strain curve of a metal. Figure 2.11 shows such a typical relationship at low strain rates (<10^2 s\(^{-1}\)) and low temperature. The deformation is uniform until the engineering stress (and the load) reaches the maximum [44]. If the material behavior follows rate independent Hollomon [45] law, which is

\[
\sigma = K \varepsilon^n
\]  

Figure 2.11: A typical stress-strain curve for a ductile material
The uniform strain $e_u$ (the strain on the material until a neck begins to form) is mostly controlled by the strain hardening exponent, $n$. If the strain rate dependence of the material is controlled by a typical rate dependent hardening law,

$$\sigma = K \varepsilon^n \dot{\varepsilon}^m \quad (2.18)$$

the same strain is controlled to a lesser extent by the strain rate sensitivity exponent, $m$ [46,47]. The strain rate hardening exponent, $m$ can also be referred to as strain rate hardening exponent. Post-uniform elongation, which is the elongation on the material since a neck is formed up to a point where it fails by rupture, is largely governed by the strain rate sensitivity exponent and ductile fracture processes [46]. So long as the strain hardening and strain-rate hardening exponents do not change as a function of strain rate, formability is not expected to be a function of strain rate or metal velocity in quasi-static isothermal tests [48].

At high strain rates ($>10^2 \text{ s}^{-1}$) and metal velocities (typically $>10 \text{ m/s}$), additional effects are to be considered. First, momentum effects make the stress distributions more complicated than would be assumed in a usual weakest link [46] or membrane analysis [49]. This can be briefly explained as follows:

In a typical high rate process, workpiece velocity will increase from the start of deformation, to a maximum value and then will progressively decrease until the end of forming or rupture. Thus, the high velocity processes are thus
different from conventional quasi-static, constant velocity (or near constant velocity) processes. While the velocity thus varies from start to finish of the forming process (on the time scale), the very nature of impact brings about spacial distribution of velocity. Velocity at the shock wave impacted surface will be much higher than the other end. This can be more readily demonstrated in a tensile test. Change from a stable deformation to unstable deformation occurs over a time period which is normally very small compared to time involved in imparting additional deformation to the mobile end. But when the cross head velocity is high (as in any high rate process), this time period becomes important, which results in additional force called inertial force, which is maximum at the center and acts in the opposite direction to the acceleration. This has been shown by many investigators to improve elongation in tensile tests [11, 37-42, 50] and improve formability in biaxial sheet forming [27]. In the electrohydraulic forming process, initially the sample is relatively uniformly accelerated in a direction normal to the plane of the sheet.

Second, when tensile tests are done at higher cross head velocities, there exists a critical velocity called von Kármán velocity [51] for a given material above which the material simply breaks near the impacted end with negligible plastic strain. This has been experimentally observed to varying degree depending upon how the material is strained. In the work of Wood et al. [27], ductility of the materials sharply decreased after a second critical velocity, which is attributed to von Kármán localization. In their results on tube bulging (as shown in Figure 2.5), the second critical velocity was not observed. This was so, since, in tube forming, all parts of the tube
circumference are strained simultaneously and there is no strain wave propagation except negligible through the tube wall. In the case of biaxial stretching, von Kármán localization was observed by Wood et al. [27]. However, von Kármán critical velocity for many materials seems to be higher than the critical velocity at which inertial effects begins to dominate. Hence, there appears to be a window of velocity regime where inertial effects could contribute to increased plasticity.

Third, non-isothermal effects such as adiabatic shear [52] can intervene producing lower instability strains than would be expected at low rates. It is well established that most of the plastic work done in a material is converted into heat. At low strain rates, there is ample time for heat to diffuse away from the deformation zone. Local rise in temperature is thus negligible. But at high strain rates, there is not enough time for the heat to flow away. So, depending upon the deformation rate and thermal diffusive characteristics of the material, temperature increases at the zones of deformation. These temperature inhomogeneities cause non-uniform straining. Since the flow stress usually decreases with increasing temperature, severe localization can take place due to dominating effects of thermal softening over strain hardening and strain rate hardening. Once intense strain localization takes place, steep strain, strain rate and temperature gradients are generated perpendicular and often parallel to the plane of localization, which change with time. Deformed material also sometimes undergoes a phase transformation. The word 'adiabatic' comes from the nature of the process that takes place in which heat generated almost fully stays within the zone of generation. This can produce premature local failure, thus decreasing the
formability of the material. Usually the strain rates and velocities commonly encountered in high velocity processes are much lower than those accompanying adiabatic localization [53,54].

Fourth, high strain rates can change fundamental constitutive behavior of the material. It has been thought that at high strain rates (typically \(>10^3\) s\(^{-1}\)) the strain-rate-sensitivity exponent of many metals approaches unity [55]. But a recent analysis suggests that these high rates increase the rate of work hardening and, at a given strain, this gives the appearance of increased rate sensitivity [56]. In either case, such a change in constitutive behavior may be expected to increase the formability of sheet metal.

Because of many of the preceding arguments, one may expect that if non-isothermal effects are not important, and if adiabatic shear bands and von Kármán velocity do not intercede, the formability of sheet metals may be improved at high velocities.
CHAPTER III

EXPERIMENTAL PROCEDURE

As outlined in earlier part of this report, investigation of possible enhancement of formability was chosen to be the main goal of current research. Electrohydraulic forming was used as a technique to generate high plastic strain rates on the material. The equipment and performance characteristics of electrohydraulic forming systems have been described earlier. Here, specific characteristics of the equipment used in the current investigation will be described.

3.1 Electrohydraulic forming set up:
A schematic circuit diagram of the equipment used is shown in Figure 3.1. It has four essential features. (1) A charging circuit to store energy in the capacitor bank (peak voltages are variable between 0 and 10 kV), (2) a capacitor bank consisting of a maximum of 8 capacitors of each 125 μF with a total capacitance of 1 mF, (3) fast action switches (ignitron switches, based on ionization breakdown) and (4) a spark gap. This simply consists of two pointed electrodes in the water filled cavity. Spark plug type electrodes are thus used to provide spark discharge under water. Current and voltage
pulses were measured using a Ragowski probe and voltage divider, respectively and this data was captured on a digital storage oscilloscope.

![Schematic circuit diagram of electrohydraulic forming](image)

**Figure 3.1:** Schematic circuit diagram of electrohydraulic forming

### 3.1.1 Capacitor bank:

The capacitor bank was fabricated by Maxwell Industries, San Diego, CA to The Ohio State University specifications (Figure 3.2). With all the eight capacitors and the maximum charging voltage of 10 kV, the maximum discharge energy available with this system is 50 kJ. Provisions were made to directly monitor the electrical characteristics of the discharge. The capital costs and physical size of capacitors are mainly controlled by their energy storage capacity. The capacitors are charged from 240 Volt mains supply via a
rectifier and step-up transformer, the voltage rating of these components being determined by the operating voltage of the capacitors. Any number of capacitors can be chosen as desired. The charging voltage can be varied continuously from 0 to 10 kV.

![Capacitor bank used in high rate experiments. The bank consists of eight capacitors of 125 μF each. Maximum voltage: 10 kV; Maximum Energy: 50 kJ.](image)

Figure 3.2: Capacitor bank used in high rate experiments. The bank consists of eight capacitors of 125 μF each. Maximum voltage: 10 kV; Maximum Energy: 50 kJ.

Functional block diagram of the capacitor bank unit is shown in Figure 3.3. When high voltage power supply is turned on, the energy storage capacitors connected to the secondary of the high voltage transformer behave like a short circuit. The current limiting resistors in the primary circuit of the high voltage transformer limit the inrush of current which would otherwise
overload the transformer. The high voltage transformer steps up the line voltage to 10 kV ac. The high voltage rectifier diodes rectify the ac output of the high voltage transformer to a dc voltage to charge the capacitor bank.

Figure 3.3: Functional block diagram of capacitor bank.

The capacitors possess specific characteristics required for high current discharge device. When the ignitrons are fired, a resonant LC circuit is formed. The effective resistance is such that several voltage and current reversals take place each time the bank is charged. With each reversal, high stresses are generated within the capacitors. Another important requirement of the capacitors is low series inductance, since all inductance (external to the
work coil in the case of Electromagnetic forming) results in lost energy. The capacitor bank used in the current investigation had a series inductance of 0.04 micro henries or less. The capacitors were designed to have a life expectancy in excess of one million operating cycles.

3.1.2 Ignitron switches:
When the pilot ignitron is fired, these supply the energy to fire the ignitron switches on the capacitor bank. Once the capacitors are charged, the charge in the capacitors is used to fire the main ignitrons. Each of these switches is a single anode rectifier with a mercury pool cathode, which can emit currents of several thousands of amperes with very low loss, because of small voltage drop in the mercury vapor arc. Stored energy is transferred to the discharge circuitry in less than 50 μs.

3.1.3 Spark gap:
The spark gap can be used as such, or a thin copper wire can be placed between the electrodes. The wire vaporizes with a small fraction of the stored energy. There are relative advantages and disadvantages of using either of these techniques. Bending the wire to conform to the geometry controls the shape of the shock wave. Thus, the discharge path can be more easily controlled and the spark energy can be more efficiently utilized. Longer gap lengths can be used with bridge wire, for a given amount of stored energy in the capacitor bank. On the other hand, operating the system with the gap, set-up time is reduced since there is no need to replace the wire after each shot. Effect of each of these techniques on the consistency of discharge was part of the early experiments and are discussed later.
3.1.4 Oscilloscope:
Capacitor discharge characteristics were recorded on a Nicolet 4094A digital oscilloscope equipped with a pair of disk drives for data storage and retrieval. Voltage and current pulses were monitored on separate channels through the oscilloscope's 100 kHz filters. The current trace was obtained by looping a Rogowski probe around an arm on the copper bus. This input was used for all triggers. A voltage divider, with a reducing factor of approximately 1:2000 and a total resistance of 200.1 mega ohms was constructed and attached to leads from the copper bus to measure the discharge voltage. Stored waveform data was transferred directly from oscilloscope on to spread sheet file in an IBM-PC using a software called "Henry" from Nicolet.

3.1.5 Electrode design:
Copper bus used in terminating cables from the capacitor bank is shown in Figure 3.4. Exploded detail of the electrode configuration is shown in Figure 3.5. The electrodes were made of copper and were covered by a sleeve made of G-10 epoxy laminated plastic. The latter was externally threaded to go in to cylindrical bottom die. The electrodes were equipped with removable threaded brass tip. Since the tip of the electrode blunted after repeated shots, they needed re-sharpening. This design facilitated replacement of just the tips without having to remove the entire electrode for re-sharpening. Teflon was first tried as an insulation material. It could not resist high forces generated and so was abandoned. The diameter of the copper electrodes was 12.7 mm. The electrodes were designed in such a way that the spark gap can be easily varied as required and be placed at the center of the die. Centering of the
spark gap in the bottom die was left to visual judgment, since it was found adequate.

Figure 3.4: Copper bus used for terminating the cables from the capacitor bank.

Tap water was used for experiments in the current investigation on the considerations of effectiveness and economy. The conductivity of water does affect the optimum gap. The lower the conductivity the narrower is the
optimum spark gap, for a given voltage. Reports in the literature show that the optimum gap with distilled water as a medium is only about half as that obtained with tap water as medium [18].

Figure 3.5: Exploded detail of the electrode configuration.

3.1.6 Stand-off distance:
Since the amplitude of the spherically expanding shock wave varies inversely with the distance from the spark gap, the amount of deformation would be expected to vary linearly with the reciprocal of stand-off distance [18]. Increased stand-off distance spreads the force over a greater area. In the
current investigation the stand-off distance was maintained through out at 76.2 mm.

3.1.7 Safety devices:
With a maximum of 50 kJ of energy discharging in a few micro seconds, the energy release rate is very high as in any high rate forming. To ensure the safety of operating personnel, several safety devices were incorporated. Safe operating practice was also formulated and rigorously followed every time the equipment was operated. These include the following:

a) Limit switches: Locks are provided in the capacitor bank compartment to prevent opening the compartment while the machine is operating. If, during charging, a door or panel is opened, the bank is automatically discharged through the within 200 milliseconds.

b) Over voltage fault: The capacitor bank charging voltage is monitored and compared with the preset energy level by a comparator circuit. If a fault occurs and the capacitor sensing circuit malfunctions and does not stop the charge, the over voltage sensing and comparator circuit takes over. It generally allows the bank to charge to 10% above preset level, then it faults the machine and releases the stored energy through a safety switch to ground.

c) Safety timing circuit: If the voltage and the over voltage sensing circuits malfunction, the timing circuit will discontinue the charging cycle, fault the machine and dump the stored energy through the dump switch to ground. The timing circuit is factory set at 6 seconds.
d) **Safety dump switch:** This switch connects all high voltage components to ground potential if

- The machine is turned off or a power failure occurs
- An interlock is opened.
- The STOP push-button is pressed.
- A machine fault occurs.

It is solenoid operated and gravity assisted.

e) **Bleeder resistor circuit:** The circuit provides a back-up safety circuit which slowly bleeds the charge from the energy storage capacitors. It also powers a neon lamp on the local control panel which indicates whenever a potential in excess of 100 volts is present on the capacitors.

f) **EMI Shield enclosures:** The machine cabinet is constructed so that the low level control and monitor circuits are mounted in an electromagnetically shielded section to provide protection from the high level discharge circuits.

g) **Shorting bar:** The capacitor shorting bar is a special resistor mounted on the end of a phenolic rod and protected by a clear lexan tube. It is used to safely ground all high-voltage capacitors and circuits before any maintenance or trouble shooting is performed. The silicon carbide resistor absorbs energies which would cause wire-wound types to open. The clear protective tube around the resistor allows visual inspection each time the bar is used. Before touching any of the electrical wiring, one should confirm that there is no energy in the capacitors. This is done by grounding the shorting bar and
touching the top of the capacitor. To disconnect a capacitor, the large charge resister must be removed from the bottom of each ignitron that is connected to a disabled capacitor.

h) **Back up dump resistors:** As a precaution against failure of the capacitor bank's dump resistors in the case of non-fire, a secondary external system was devised. Two 1000 ohm power resistors were wired in series between the terminals of the copper bus. Insulated brackets and a separate base were constructed on which the resistors could be mounted alongside the other equipment. Although never required as a sole means of discharge, these resistors proved to be quite effective as a primary means of dissipating energy when the current failed to bridge the spark gap.

i) **Enclosure:** The most important precaution taken against mechanical or explosive hazards was the construction of a protective enclosure for the die and electrode assembly. It was known from previous work that the forming process was capable of breaking the bolts which held the die and its components together. The enclosure, shown in Figure 3.6 was designed with two purposes in mind. It could be used in the horizontal position (as shown) with the coaxial electrode setup or vertically with the parallel electrode arrangement.

There was initially some concern over the magnitude of the vibrations which would be transmitted to the floor and surrounding area but these turned out to be negligible. Hence, the enclosure and the die were placed directly on the table containing the copper bus with no adverse effects. The enclosure itself
was constructed out of 6.25 mm thick welded mild steel with 25.4 mm thick rubber sheet bolted to the inner walls.

Figure 3.6: Protective enclosure used in the electrohydraulic forming.
3.2 Low rate forming setup:

![Diagram of low rate forming setup]

**Figure 3.7:** Experimental set up for low rate forming

Comparative studies at conventional forming rates were carried out by increasing the volume of oil in the cavity using a hydraulic pump. The schematic of the procedure is shown in Figure 3.7. The upper die used in these experiments was the same conical die used in high rate experiments. The lower die was cylindrical with inlet port for pumping hydraulic oil. Electrically operated pump was used to fill the lower die with oil. After filling the lower die with oil, the circular workpiece was placed, ensuring that there was no entrapped air beneath it. The top die was then placed over the sample and was fastened to the bottom die through the sample using 12 bolts around
the circumference. This was done to ensure that the sheet metal would undergo nearly pure stretching with little draw-in. The pump was capable of generating pressures up to 70 MPa. Actual pressures were monitored using a pressure gage. In all the cases, the work piece failed before it could get to fill the conical die completely. When failure occurred, oil leaked through the hole at the apex of the die and the pressure dropped suddenly. It may be noted that the same hole at the apex was used as a vacuum port in the high rate experiments. In the low rate experiments, it was found that evacuation of air above the sample was not necessary.

3.3 Choice of materials and their properties:
Materials chosen for the current investigation were Interstitial Free Iron (IF Iron), Oxygen Free High Conductivity Copper (OFHC Copper) and 6061 Al-Si-Mg alloy in T4 condition. These materials are commonly used in conventional sheet forming applications and have been well studied at low strain rates and velocities. IF iron sheets were supplied by ARMCO and the properties are as shown in Table 3.1. The chemical composition and mechanical properties were determined and were provided by ARMCO [57].

OFHC copper sheets in thicknesses of 0.79 mm and 0.34 mm were used in the experiments in annealed condition. Tensile tests were carried out in both longitudinal and transverse directions to characterize the mechanical properties. These are shown in the next chapter.

Aluminum alloy used in the experiments were in thicknesses of 1.6 mm. Since formability of this alloy is poor in T6 (Solution heat treated and
artificially aged) condition, the sheets were heat treated to produce T4
(solution heat treated and naturally aged) temper. Solutionizing was done by
heating the sheet metal to 530° C, soaking them for 40 minutes as
recommended in the literature [59]. The sheets were quenched in water kept
at room temperature. Quench delays were kept well below the allowable 10 s.
To ensure attainment of stable mechanical properties, the sheets were
allowed to age naturally for at least 7 days prior to forming. Mechanical
properties were determined by tensile tests and are shown in the next chapter.

<table>
<thead>
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<th>Chemical Composition:</th>
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<td><strong>C</strong></td>
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Thickness: 0.84 mm

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<tr>
<th>Mechanical Properties:</th>
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</thead>
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<tr>
<td><strong>Yield Strength(0.5%):</strong></td>
</tr>
<tr>
<td><strong>Yield Strength(0.2%):</strong></td>
</tr>
<tr>
<td><strong>Tensile Strength:</strong></td>
</tr>
<tr>
<td><strong>Total elongation:</strong></td>
</tr>
</tbody>
</table>

Table 3.1: Properties of interstitial free iron used in the experiments.
3.4 Grid marking procedure:

In order to measure the strains at various locations of the sheet metal after deformation, the surface of the sheet metal was marked with a grid of circles before forming. After deformation, the circles would distort into ellipses. Changes in major and minor axes of ellipse from the original diameter of the circle represent major and minor in-plane strains on the sheet metal. By conservation of volume, thickness strain can be calculated.

Preliminary attempts to make grid marking by photo etching was found unsatisfactory. The grid markings were found erased after forming. This could have been due to two factors. First, the strains encountered in electrohydraulic forming are very high which stretched the grid circle accordingly. Also the speed at which the sheet metal strikes the die is a few hundreds of meters per second. At such high speeds, the work piece was found to stick to the die with grid marks almost wiped out. Hence, electrolytic etching was used to make the circle grid. Electrolytic etching was done using “Lectroetch” portable unit. In this process, a controlled low voltage current etches out the metal in the presence of electrically conductive electrolyte fluid. Permanent marks are made in seconds by means of a stencil containing the circle of grids. Both electrolyte and electric current reach the metal surface through openings in the stencil. Only the mark detail fixed in the stencil is etched into the metal surface.

The equipment consists of a power unit to provide DC or AC supply, a rocker pad which is used to apply manual pressure to make the grid marking.
electrolytic solution and connecting cables. The procedure consists of the following steps:

1. Rocker pad is first connected to the power unit. Another lead is connected to a base metal sheet. Stainless steel sheet was used to avoid corrosion.
2. The sheet to be grid marked is placed on top of the base metal with the surface to be gridded facing up.
3. The grid is then aligned on top of the sample over which a wick pad is placed.
4. About two spoonsful of appropriate electrolyte is poured on the wick pad.
5. The power is then turned on and the rocker pad is placed on top of the wick pad and rocked with gentle hand pressure. Duration and hand pressure are arrived at after a few trial and error.

In the current experiments, V-45A power unit was used to provide power supply. AC setting was used. The stencil had a grid of circles with a diameter of 2.54 mm. Specific “Lectroetch” electrolytes were employed for each of the materials used.

3.5 Strain and strain distribution measurements:
Grid circle dimensions before and after forming were measured using a traveling microscope with a digital read out and a precision of 0.001 mm. The microscope provided a magnification of 10X. Strain distribution was measured on axisymmetric samples produced using conical die, hence it is along the curved surface from the bottom to the top of the cone. Small strain formulation was used.
3.6 Die geometries:

Formability experiments were carried out using a conical die. The conical die provided one of the severest geometries for sheet metal forming. For common sheet thicknesses of 0.5 to 2.0 mm and a discharge capacity of 50 kJ, the die dimensions were chosen as shown in Figure 3.8 with the expectation that fracture would always occur in conventional forming. The photograph
showing the actual experimental set up is shown in Figure 3.9. The apex angle of 90° was chosen for simplicity. Truncated conical geometries and rectangular dies were also used in the latter stages of the work to demonstrate that severe geometries could be easily formed at high rates. The same female die was used in every case whenever the high rate experimental results were compared to that at conventional low rate.

![Image of setup](image)

**Figure 3.9:** Photograph showing the actual die set up at high rate.

### 3.7 Velocity measurement system:

The conical die was fitted with Infrared Light Emitting Diodes (IREDs) at predetermined heights along the curved surface. Photo transistors (PTs) were fitted diametrically opposite to the IREDs. When the sheet metal is deformed, it progressively blocks the path of IRED-PT pair. With the help of a logic box,
this event is translated into step-in voltage. Thus, for every IRED-PT pair blocked, there will be a step in voltage which is captured in a digital oscilloscope. The time interval between the steps is measured. Knowing the separation between IREDs, mean velocity of the metal can be calculated. The location of each of the IREDs and PTs is shown in Figure 3.10. The detailed arrangement of fitting these into the die is shown in Figure 3.11. The specifications of IREDs and PTs are shown in Table 3.2.

![Image](image_url)

**Figure 3.10:** Die used in the forming operations showing the locations of IREDs and PTs.

IRED is mounted with the anode soldered to the center pin of the coaxial connector. The cathode (longer lead) of the IRED is soldered to the outer metal. The PT is mounted with the collector soldered to the center pin and the emitter (longer lead) to the outer metal of the coaxial connector. Rubber silicone sealer is used to cover the leads from the base of the coaxial connector. This kept the forming liquid (water) from entering between the leads (and possibly causing any disturbance) and also made cleaning of the
IRED-PT unit easier. The IRED-PT unit is then inserted in to a Teflon casing, where it is held in place by the nut on the bottom of the co-axial mount. The coaxial cables are preferably of the same length, but enough to keep the logic box and oscilloscope away from the capacitor bank. The circuitry is shown in Figure 3.12. The logic box is to ensure that measurable signals are obtained in the form of voltage steps. The IREDs are named A, B, and C from bottom to the top of the die. Matching PTs are named a, b, and c in the figures.

![Diagram](image)

**Figure 3.11:** Assembling sequence of IREDs and PTs before inserting into the forming die.
<table>
<thead>
<tr>
<th>Description of the Part</th>
<th>Local Source</th>
<th>Manufacturer</th>
<th>Part No.</th>
<th>Quantity</th>
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</thead>
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<tr>
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<td>Archer</td>
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<td>2</td>
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<td>Archer</td>
<td>278-220</td>
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<td>Archer</td>
<td>64-2314B</td>
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<td>6 Ω Resistor</td>
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<tr>
<td>Type F-59 Coaxial Cable</td>
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<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3.2: Components used in the velocity measurement system.
After ensuring that all the connections are made as described above, the forming experiment is set up and performed. The typical voltage characteristic in a forming experiment is as shown in Figure 3.13. As the metal workpiece blocks the optical path of IRED-PT pairs progressively one after the other, the steps in voltage are created. The voltages were a few hundred millivolts for the set up used in the experiments using a 6 volt battery. The distance between two consecutive steps in voltage are measured to arrive at the time the workpiece takes to travel between the corresponding two IRED-PT pairs.

Let the average velocity of metal between initiation of forming and IRED-PT pair A-a be $V_1$.

Average velocity of metal between IRED-PT pair A-a to B-b = $V_2$.

Average velocity of metal between IRED-PT pair B-b to C-c = $V_3$. 

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Distance from sample to A-a = 15.24 mm
Distance between A-a and B-b = 20.32 mm.
Distance between B-b and C-c = 6.35 mm.

If the corresponding time steps measured in milli seconds are $t_1$, $t_2$ and $t_3$
then $V_1 = \frac{15.24}{t_1}$ m/s
and $V_2 = \frac{20.32}{t_2}$ m/s
and $V_3 = \frac{6.35}{t_3}$ m/s

This system of measuring the metal velocity posed some problems in high rate experiments. These aspects are discussed later.

Figure 3.13: A typical voltage vs. time characteristic
3.8 Tensile tests:
The sheet metals used in the forming experiments were tested for their tensile properties in an Instron machine. Tensile samples were prepared using Tensilkut machine. Starting width of the sample was 12.32 mm. The deforming length was 69.85 mm. The cross head velocity was $6.985 \times 10^{-3}$ mm/s. The engineering strain rate was $1 \times 10^{-3}$ s$^{-1}$.

3.9 Terminal hardness measurements:
Final hardness of a sheet metal after forming is one of the important indicators of practical significance in metal forming operations. It provides in simple terms the extent of work hardening on the material, and hence can be used to decide whether subsequent operations can be performed on the component without intermediate annealing. As it will be brought about later, this information can also be used in the current investigation to draw inferences on possible mechanisms behind the improved formability observed in electrohydraulic forming.

The micro hardness was measured using a Vickers indentor at various locations on the high and low strain rate samples. The formed components were cut into small pieces with known major and minor strains, from which thickness strains were calculated. This method was preferred to directly measuring the thickness of the sample due to two reasons: (1) the errors in the measurement of thickness strain due to initial variation in the thickness of the sheet metal are eliminated; (2) thickness strain in biaxial stretching reflects Tresca effective strain if both the in-plane strains are tensile. Knowledge of major and minor strains accompanying each thickness strain
helped ensure that it was indeed so. These samples were metallographically prepared and measured for hardness in Vickers micro hardness Tester.

The load used for IF Iron was 500 g and the loading duration was 15 seconds. The indentation was of the order of 90 μm. In the case of copper, the load was 200 g and loading duration was 10 seconds. The indentation was of the order of 60 μm. The load used for aluminum was also 200 g and the duration was also for 10 seconds.
CHAPTER IV

EXPERIMENTAL RESULTS

4.1 Effects of discharge energy:
Wave form traces of voltage and current were recorded upon discharging the capacitor bank. For successful discharges, the curves proved to be well behaved and consistent. As a result, the general success of a given forming attempt could be evaluated on the basis of the traces alone. Any problems upon firing, such as difficulty in bridging a spark gap or improper firing of an ignitron, were readily apparent as deviations from the expected behavior. Wave form traces of both current and voltage were changed and sometimes did not appear. A typical good trace is shown in Figure 4.1. This trace was taken during forming of a copper sheet at 25 kJ energy level at a spark gap of 1.59 mm (1/16\textquotedbl). Most variations in the wave form characteristics due to different forming parameters occurred over a limited range. Observed oscillations varied in frequency from 4 to 12 kHz and lasted 1.5 to 2.5 cycles.

If the spark gap was excessively large or other parameters made the initiation of a good spark difficult such as blunt electrodes, low conductivity water etc., then the shock wave had a low intensity (and little ability to deform metal). Such conditions also correlated well with the oscilloscope traces. In general,
cycle periods greater than 120 μs and peak currents above 60 kA correlated with good discharges as illustrated in Figure 4.2. This demonstrates that easily obtained data can be quite useful for in-process monitoring.

Figure 4.1: Typical discharge characteristics. Discharge Energy: 25 kJ.

The extent of metal deformation depends on the strength of the shock wave which in turn depends on the discharge energy [60]. As the discharge energy was increased, the sheet metal was able to fill the conical die progressively to a larger extent. Beyond some optimum energy, the sheet metal started to tear up at the center part. When the energy was increased further, the torn part of sheet metal balled up and fell inside the forming chamber. Typical shapes of components formed when the energy was progressively increased are shown in Figure 4.3.
Figure 4.2: Cycle period and peak current as a function of spark gap. All the eight capacitors were used. If the spark gap was 6.25 mm or more, little forming would result (Data from Ref. 61).

Figure 4.3: Effect of insufficient or extra forming energy.
4.2 Effects of spark gap and bridge wire:
As mentioned earlier, electrohydraulic forming can be done with a simple spark gap or with a thin bridge wire connecting them. The effects of bridge wire on the forming characteristics were evaluated by forming 0.34 mm copper sheet using the conical die described earlier. The bridge wire used was 0.58 mm in diameter. The discharge energy was kept constant at 25 kJ, using all the eight capacitors. The copper sheets filled the die progressively to a lesser extent when the spark gap was increased from 1.59 mm (1/16") to 7.94 mm (5/16"), as shown in Figure 4.4. On the contrary, when the bridge wire was used to fill the spark gap, the extent of forming did not change with spark gap appreciably as shown in Figure 4.5.

![Figure 4.4: Variation of forming with spark gap. Energy used was 25 kJ. Spark gaps used were (from left to right in the above figure) 1.59 mm, 3.18 mm, 6.35 mm and 7.94 mm.](image)
Figure 4.5: Forming at different spark gaps using bridge wire. Energy used was 25 kJ. Spark gaps used were (from left to right in the above figure) 3.18 mm, 6.35 mm and 9.53 mm. Bridgewire of 0.58 mm diameter was used to fill the spark gap.

These conclusions are more readily apparent when the discharge characteristics are compared. Figure 4.6 shows that the discharge characteristics changed appreciably when spark gap was changed from 1.59 mm (1/16") to 7.94 mm (5/16"). On the contrary, the discharge voltage and current remained nearly the same over a range of spark gaps, when a bridge wire was used as shown in Figure 4.7.
Figure 4.6: Oscillograph for discharges across various spark gaps. The thin line in the above figure represents the discharge current and the thick line represents the discharge voltage. Spark gaps used were (a) 1.59 mm, (b) 3.18 mm, (c) 4.76 mm and (d) 6.35 mm. Energy was kept constant at 25 kJ in all cases. Notice that the traces varied significantly with the spark gap.
Figure 4.7: Oscillograph for discharges across various spark gaps with bridge wire across the gap. The thin line in the above figures represents the discharge current and the thick line represents the discharge voltage. The gap between electrodes were (a) 3.18 mm, (b) 6.35 mm and (c) 9.53 mm. The traces did not vary appreciably. Energy was kept constant at 25 kJ in all cases.
4.3 Comparison of low and high rate forming results:

Based on the above results, subsequent forming experiments were carried out always with the bridge wire of dimensions described above [62, 63]. The spark gap was kept the same at 6.35 mm and in order to be consistent, all the eight capacitors were used. There have been many suggestions in the literature that the air entrapped in the female die above the sheet metal workpiece must be removed prior to the forming operation. In all the experiments in this work, a hole was provided at the apex of the conical die and a vacuum pump was connected to it to evacuate the air before forming. Sheet metal samples of Interstitial Free Iron, Copper and 6061 T4 Aluminum were formed using electrohydraulic forming. Discharge energy was progressively increased from one forming attempt to another until the sheet could fill the conical die completely. Energy was varied by varying the charging voltage. Low strain rate comparison tests were done by pumping oil into the cavity to push the metal into the conical die.

4.3.1 Visual comparison:

Figure 4.8 shows the shapes of IF iron sheets formed under electrohydraulic and quasi-static conditions. Sample formed electrohydraulically showed significantly higher dome height than the one formed at low strain rates. The optimum discharge energy required to achieve this improvement was 35 kJ. Failure at the apex region was unavoidable due to the presence of vacuum port there.
Figure 4.8: Interstitial Free Iron samples formed at low (left) and high (right) rates. Discharge energy used at high rate was 35 kJ.

Copper samples also showed similar increase in formability at a discharge energy of 20 kJ as shown in Figure 4.9. The sample could fill the conical die completely at high rate. The most dramatic increase was observed on 6061 T4 Aluminum (Figure 4.10). Heights of the samples at low rate and high rate are compared in Table 4.1.

Figure 4.9: Oxygen free high conductivity copper samples formed at low (left) and high (right) rates. Discharge energy used at high rate was 20 kJ.
Figure 4.10: Aluminum 6061 T4 samples formed at low (left) and high (right) rates. Discharge energy used at high rate was 25 kJ.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample Height in mm</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Low Rate</td>
</tr>
<tr>
<td>6061 T4 Aluminum</td>
<td>35.4</td>
</tr>
<tr>
<td>Copper</td>
<td>36.8</td>
</tr>
<tr>
<td>IF iron</td>
<td>38.8</td>
</tr>
</tbody>
</table>

Table 4.1: Heights of sheet metal samples formed at low and high rates

4.3.2 Forming Limit Diagrams (FLD):

Forming Limit Diagram(FLD) is a representation of in-plane principal strains withstood by the sample without failure. It is a very useful tool to represent and analyze the maximum principal strains in an actual sheet formed component. Major and minor strains are measured on the sample and represented on a two dimensional plot. Forming Limit Curve is drawn
through the maximum values of major and minor strain combinations observed without failure. Limit strain combinations observed in actual metal forming operations are compared against predetermined FLD to predict possible failure.

Forming Limit Diagram for IF Iron was provided by ARMCO [57] for the sheets used in the current investigation. This is shown in Figure 4.11. The diagram is presented in terms of engineering strains. The diagram contains three zones: Safe Zone, Marginal Zone and Necking Failure Zone. If a strain state is in the Safe Zone, no failure should occur in that area with the forming conditions present at the time the circle gridded panel was formed. The Marginal Zone is a safety band (10% major strains usually) to allow for fluctuations in the forming process. Areas with strains states in the marginal zone should not fail if the forming process is well controlled. An effort should be made to avoid strain states in the Marginal Zone during new die development to ensure that failures do not occur as the tool wears. Areas of the sample with strain states falling in the Necking Failure Zone are subject to periodic failure by fracture or local necking. The lower border of the Necking Failure Zone is the Forming Limit Curve and indicates at what strain states local necking may begin. The limit strain on the Forming Limit Curve corresponding to zero minor strain represents plane strain forming limit, which is frequently referred to as FLD₀. Formability of the sheet metal is poorest in this strain state and hence it represents the most severe forming condition. The shape of the FLD is similar for all low carbon steels, and moves very slightly vertically along the major strain axis as a function of thickness and strain hardening exponent, n. The forming limits of IF iron
have been reported to change little with strain rate during conventional sheet forming [64].

Figure 4.11: FLD for IF iron from ARMCO (Data from Ref. 57) and added data from low and high rate forming experiments. All the strains are engineering strains. Small strain formulations were used.
Also shown in the same figure (Figure 4.11) are the principal strains measured on the high and low rate samples. The principal strains measured on the low rate samples confirmed more or less the forming limits determined by ARMCO. These are shown as "low rate data" in the figure. Similar strain measurements on the high rate sample are represented in the figure as "high rate data." It may be noted that strains well above 100% have been observed on the high rate sample away from fracture. The high rate samples withstood major strains in excess of 100% without failure even under nearly plane strain conditions. The ARMCO FLD drawn at low rate would have predicted that such high major strains would cause definite necking failures, while the results showed otherwise. The high rate results suggest as if the FLC were shifted up to a much higher major strain as approximately indicated in Figure 4.11.

The published FLD and superimposed strains from low and high rate samples for OFHC Copper are shown in Figure 4.12. The published FLD for this material [65] is shown by continuous line. The principal strains measured on the low rate samples more or less confirmed the published forming limits. In this case too, like in IF iron, major strains in excess of 100% were observed without failure on the high rate sample. The conventional FLD would have predicted necking failure at such high strains. Once again it appears as if the FLD at high rate was at a much higher major strain than the conventional one as approximately indicated in Figure 4.12. It must be noted that strains near the apex in the high strain rate conical sample could not be measured, since the grid markings were erased after forming.
Figure 4.12: FLD for OFHC Copper (Data from Ref. 65) and added data from low and high rate forming experiments. All the strains are engineering strains. Small strain formulations were used.
Figure 4.13: FLD for 6061 T4 Aluminum (data from Ref. 66) and added data from low and high rate forming experiments. All the strains are engineering strains. Small strain formulations were used.

The published FLD for 6061 T4 Aluminum [66] is shown in Figure 4.13, with superimposed strains from low and high rate samples. The low rate data more or less confirmed the published forming limits. However, the strains observed on high rate samples were once again well above 100%, which
would fall in the necking failure zone of conventional FLD. The suggested approximate location of high rate FLD is also shown in Figure 4.13.

From the above results, it is clear that the formability of sheet metals dramatically increases at very high rates. It must be noted that in all the high rate experiments, not only the strain rates were higher, but also the metal velocities. It is important to understand this difference. As will be discussed later, momentum effects arise due to high metal velocities, but not necessarily at high strain rates. Changes in material constitutive behavior are often associated with high strain rates. Until the origin of increased formability is satisfactorily resolved, the convention followed in this report is to refer to the experiments as "high rate" and "low rate." When specific metal velocities or strain rates are compared, the experiments may be referred to as "high metal velocities" and "low metal velocities" or "high strain rate" and "low strain rate."

4.3.3 Plane strain forming limits:
Even though the photographs and the FLD data convey the extent of formability improvement quite clearly, comparison of plane strain forming limits is the most critical examination of the data. This is due to the fact that failures most commonly take place near plane strain conditions. Fracture strains were analyzed from the high strain rate data on each of the metal systems to pick the major strain closest zero minor strain. This was compared against the major strain of the published FLD corresponding to the same minor strain as was in high rate and is shown in Table 4.2. It is clear from the
data that even the near plane strain forming limit increased at least 2.5 times in IF iron and Copper and over 5 times in the case of 6061 T4 Aluminum.

<table>
<thead>
<tr>
<th>Material</th>
<th>High strain rate</th>
<th>Low strain rate</th>
<th>Relative major strains (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Minor strain</td>
<td>% Major strain</td>
<td>% Minor strain</td>
</tr>
<tr>
<td>IF Iron</td>
<td>1.1</td>
<td>100.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Copper</td>
<td>4.0</td>
<td>65.6</td>
<td>4.0</td>
</tr>
<tr>
<td>6061 T4 Al</td>
<td>3.0</td>
<td>122.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 4.2: Comparison of improvement in near plane strain forming limits.

4.4 Terminal hardness results:
Microhardness was measured as a function of strain by a procedure outlined earlier. The strain was plotted as a function of true thickness strain. This is exactly the Tresca effective strain, since both the in-plane strains were tensile for all of the data represented in the Figures 4.14 to 4.16. In the case of IF iron, the hardness of high rate sample was slightly lower than that of the low rate sample. Aluminum and Copper both exhibited slightly higher hardness at high rate at all values of strain. However, the difference in hardness between low and high rate samples at any given strain was always less than 20%.
Figure 4.14: Microhardness of IF iron as a function of strain at low and high rates. Hardness of as-received material: 104.8 HV.

Figure 4.15: Microhardness of OFHC Copper as a function of strain at low and high rates. Hardness of as received material: 72.9 HV.
Figure 4.16: Microhardness of 6061 T4 Al as a Function of Strain at Low and High Rates. Microhardness of as received material: 47.6 HV.

4.5 Tensile test results:
Tensile test results on 0.84 mm Interstitial Free Iron was provided by ARMCO [57]. These results have been shown earlier in this report. The data were used to fit to Hollomon law as follows:

\[ \sigma = K \varepsilon^n \]  

(4.1)

\( \sigma \) is true stress, \( \varepsilon \) is true strain and \( K \) is the strength coefficient. For IF iron, \( K \) was found to be 544 MPa and \( n = 0.236 \).

Tensile test were performed on OFHC copper samples used in this investigation according to the procedure described earlier. Tests were carried
out in both rolling and transverse directions and are shown in Figure 4.17. When Hollomon law was used to fit the data the value of K was 365 MPa and n was 0.217.

![Graph showing true stress vs. true strain curve for OFHC copper](image)

**Figure 4.17:** True stress vs. true strain curve for OFHC copper used in the experiments.

The 6061 T4 Aluminum sheets used in the experiments were also similarly tested. The Hollomon coefficients for the data were K=176 MPa and n=0.23.

### 4.6 Velocity measurements:

In order to facilitate analysis of formability results, attempts were made to measure the metal velocity at high and low rate forming experiments. As a
simple and cost effective means, Infra-red light Emitting Diodes and Photo transistors were used to measure metal velocity as described earlier.

In all the low rate experiments, the work piece could never fill the die completely. So, the upper most IRED-PT pair in Figure 3.8 was never blocked. Thus, velocity could be measured in two intervals. $V_1$ is the average velocity during initial stage of forming and $V_2$ at the later stage. The time interval and respective velocities for each of the metal systems is shown in Table 4.3. All the low rate samples failed within 3 mm after crossing the B-b pair of IRED-PT. Assuming the metal velocity to be $V_2$, time elapsed between the B-b pair and end of forming can also be estimated. This, when added to $t_1$ and $t_2$ yields the total time taken for forming. This is also a useful quantity and is listed in Table 4.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>$t_1$ (s)</th>
<th>$t_2$ (s)</th>
<th>$V_1$ (mm/s)</th>
<th>$V_2$ (mm/s)</th>
<th>$t_{total}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF Iron</td>
<td>2.96</td>
<td>5.49</td>
<td>5.14</td>
<td>3.71</td>
<td>9.32</td>
</tr>
<tr>
<td>OFHC Copper</td>
<td>3.38</td>
<td>5.75</td>
<td>4.51</td>
<td>3.53</td>
<td>9.48</td>
</tr>
<tr>
<td>6061 T4 Al</td>
<td>2.69</td>
<td>4.7</td>
<td>5.67</td>
<td>4.32</td>
<td>7.39</td>
</tr>
</tbody>
</table>

Table 4.3 Average metal velocities during early and later stages of low rate forming.
Similar measurements of velocity at high rates met with various experimental problems. The stepped voltage generated by the blocking of IRED-PT was a few milli volts. These small signals were masked by large amounts of electromagnetic noise generated by the high voltage electric discharge during the high rate forming. However, as is shown later, there are various analytical methods available that could be used to estimate metal velocities and strain rates in high velocity metal forming.

4.7 Demonstration of other shapes:

In order to compare the ability to produce sharp corner between conventional and high rate forming processes, a truncated conical shape was chosen. A new die was made as shown in Figure 4.18. It consisted of three parts. The outer most part was kept to the same diameter as the conical die used earlier (shown in Figure 3.8), so that it fit the bottom die. This part also carried the vacuum port. The innermost part was made to the desired shape of the component to be formed. To enable easy attachment, the middle piece was required in this composite die. To try out a new shape, only the inner most insert needed to be changed, and thus quick tryout of various shapes was made possible. A truncated conical shape formed using this die in 6061 T4 Aluminum is shown on the right in Figure 4.19. The starting material was commercially available 1.27 mm thick 6061 T6. This was solution treated at 510°C for one hour and then water quenched. Samples used for all trials under this experimental plan were naturally aged for 2 weeks. The material was able to fill the die without failure around the sharp corner. Six capacitors and a discharge energy of 22.5 kJ were used in electrohydraulic forming with bridge wire. In the above experiment, the sheet metal was clamped all
around to prevent draw-in of the material. Thus the sharp corner was accomplished in pure stretching. A close up view of the sharp corner produced at high rate is shown in Figure 4.20.

Figure 4.18: Three piece die used for forming truncated conical shapes
Figure 4.19: Corners produced at low (shown on left) and high (shown on right) rates using a conical die with 45° semi-apex angle. Sheet thickness: 1.27 mm. Material: 6061 Aluminum - T4. Hydraulic pressure at low rate: 22 MPa. Six capacitors and 22.5 kJ discharge energy were used at high rate.

Figure 4.20: Close-up view of the sharp corner formed at high rates.
Similarly prepared material was formed at conventional low rate using the hydraulic pump described earlier. After a pressure of about 13.5 MPa, the oil started leaking between the top and bottom dies as well as through the bolts used to tighten the sheet metal all around. The experimental set up was improved by using a copper seal between the dies. Torque on the bolts was increased to 27 N-m. The equipment could now hold a pressure of up to 22 MPa. Sample formed under these conditions is shown on the left in Figure 4.19. It can be seen that the high rate process could produce a very sharp corner compared to similar sample produced at low rate.

In order to verify that very high plastic strains are possible in non-axisymmetric shapes as well, a rectangular cavity was used. The complete top die assembly is shown in Figure 4.21. The starting sample was commercially available 2.03 mm thick 6061 Aluminum in T4 condition. It was solutionized at 510°C for one hour and then water quenched. Within half hour of quenching, the sheet sample was subjected to forming to prevent the effects of aging. The sample was formed at high rate in electrohydraulic forming using six capacitors and a discharge energy of 26.25 kJ. Once again, pure stretching was ensured by clamping the sheet all around. It can be seen from Figure 4.22 that the sample was successfully formed. Strains near 100% in nearly plane strain conditions were measured. These measured strains far exceed those predicted as being safe in a usual forming limit diagram.
Figure 4.21: Die used in forming rectangular shape component
Figure 4.22: Rectangular box-like component formed at high rate in electrolydraulic forming.

No. of capacitors: 6; Discharge energy: 26.25 kJ

Material: Solutionized 6061 Aluminum; Thickness: 2.03 mm.

In order to estimate the extent of spring back, the sample was put back into the die and was tapped. It felt solid, which implied that the spring back was negligible. It must also be noted that in almost all of the high rate experiments, the finished component was found stuck very closely to the die, which indicated that the spring back was negligible. The rectangular cavity was 50.8 mm by 25.4 mm in cross section and a height of 12.65 mm (0.4980”). The sample height measured 12.60 mm (0.4960”). Thus the spring back was less than 0.5 mm (0.002”).
4.8 Surface replication experiments:

High rate processes are capable of excellent surface reproduction. In order to demonstrate this effect, the conical die shown in Figure 3.8 was inserted with a steel block to produce the shape of truncated cone. Two concentric circular grooves were machined on the steel insert. The material used was 1.6 mm thick 6061 Aluminum in T6 (full hard) condition. As before, the sheet metal was clamped all around to ensure pure stretching. Small tearing was observed on the edge of the groove with largest diameter as well at one spot at the base of the sample. It can be seen from Figure 4.23 that the sheet metal could form with excellent reproduction of the machined grooves on its top surface. This also demonstrates that materials with limited ductility can be formed this way. This improves component strength to weight ratios, while allowing higher precision in formed shapes.

All the above examples show that dramatic formability improvement is possible at high rates, in addition to excellent reproduction of intricate surface details and sharp corners.
Figure 4.23: Component formed in 6061 Aluminum in T6 condition in 
Electrohydraulic forming. The top surface shows replication of 
machined grooves on the die. Sheet thickness: 1.6 mm. All 
the eight capacitors were used.
CHAPTER V

MODELING

From the experimental results, it is clear that dramatic improvements in formability can be expected at high rates. The phenomenon that increasing forming velocity increases formability still appears to be poorly understood. It has been argued earlier in this report that possibilities of increasing biaxial formability exist under the following conditions.

(a) when the metal velocity is high enough for inertial (alternatively referred to as momentum) effects to be large,

(b) and at the same time when the velocity is not high enough or geometry not appropriate for von Kármán localization to set in,

(c) when non-isothermal effects such as adiabatic localization do not intercede.

In order to sustain these arguments, it is necessary to estimate metal velocities in high rate experiments and show that they are large enough for inertial effects to be appreciable and to demonstrate that inertial effects can provide improved formability.
5.1 Estimates of velocity at high rates:

The velocity measurement set up described earlier could be successfully used in all the low rate experiments. However, it could not be used to measure velocities in electrohydraulic forming, since the signals (~ few mV) were lost in the noise produced by the high voltage circuitry. In order to compare the present experimental data and the model, some estimates of the workpiece velocity are needed. Several approaches are possible.

5.1.1 Energy balance approach:

In deforming from a flat sheet to a cone, the surface area of the test sample increases. From constancy of volume in plastic work, this ratio can be equated to reciprocal of thickness ratio as shown below:

\[
\frac{t_0}{t_f} = \frac{\sqrt{r^2 + h^2}}{r}
\]

(5.1)

Figure 5.1 Change of surface area of sheet sample while deforming through a conical female die.
Where \( t_f \) is the final average thickness of the sample and \( t_0 \) is the original thickness of the sample. From this, average strain on the sample is calculated as follows:

\[
\frac{1}{E} = \ln \left( \frac{t_0}{t_f} \right) = \ln \left( \frac{\sqrt{r^2 + h^2}}{r} \right)
\]  

(5.2)

The area under the stress-strain curve multiplied by the volume of metal in the cone, gives an estimate of the useful plastic work by the shock waves on the diaphragm. These are computed for each of the material studied, and are shown in Table 1. This represents about 2% of the energy available in the electrical discharge. To estimate the metal velocity and the strain rate on the sample, we assume that initially the forming energy (for example, 803 Joules for IF Iron) was given to the sample as kinetic energy. By this the initial velocity is estimated.

\[
\frac{1}{2} \rho \, v^2 = \text{Plastic Work/unit volume}
\]

(5.3)

If a rate independent Hollomon type of material behavior is assumed, typical constitutive equation is \( \sigma = K \varepsilon^n \), where \( \sigma \) is stress, \( \varepsilon \) is strain and "n" is the strain hardening exponent of the material. Since the attempt here is to estimate the strain rate in the first place, increase in flow stress due to high strain rate is neglected.

\[
\text{Plastic work/unit volume} = \int_{\varepsilon_0}^{\varepsilon} \sigma \, d\varepsilon = \int_{\varepsilon_0}^{\varepsilon} K \varepsilon^n \, d\varepsilon = \frac{K}{n+1} \left[ \varepsilon^{n+1} \right]_{\varepsilon_0}^{\varepsilon}
\]
Therefore, \[ V = \sqrt{\frac{2}{\rho} \left( \frac{K}{n+1} \left[ \frac{\varepsilon^{n+1}}{\varepsilon_0} \right]^{\varepsilon} \right)} \] (5.4)

If this velocity is assumed to decrease linearly with time as the sample filled the die, the total time consumed in forming can be calculated.

Time taken for forming = \( \tau = 2 \times \frac{h}{V} \)

\[ \text{Strain rate} = \frac{\varepsilon}{\tau} \] (5.5)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IF iron</th>
<th>Copper</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius, ( r ) ((10^{-3} \text{ m}))</td>
<td>50.80</td>
<td>50.80</td>
<td>50.80</td>
</tr>
<tr>
<td>Thickness ( t_0 ) ((10^{-3} \text{ m}))</td>
<td>0.84</td>
<td>0.79</td>
<td>1.60</td>
</tr>
<tr>
<td>Volume, ((10^{-6} \text{ m}^3))</td>
<td>6.810</td>
<td>6.405</td>
<td>12.972</td>
</tr>
<tr>
<td>Height, ( h ) ((10^{-3} \text{ m}))</td>
<td>50.65</td>
<td>51.33</td>
<td>51.84</td>
</tr>
<tr>
<td>Average True effective strain</td>
<td>0.345</td>
<td>0.351</td>
<td>0.357</td>
</tr>
<tr>
<td>Strength Coefficient, ( K ) ((\text{MPa}))</td>
<td>544</td>
<td>365</td>
<td>176</td>
</tr>
<tr>
<td>Strain hardening exponent, ( n )</td>
<td>0.236</td>
<td>0.217</td>
<td>0.23</td>
</tr>
<tr>
<td>Plastic work/unit volume ((\text{MJ}))</td>
<td>117.917</td>
<td>83.721</td>
<td>40.148</td>
</tr>
<tr>
<td>Density ((10^3 \text{ kg/m}^3))</td>
<td>7.8 [67]</td>
<td>8.92 [68]</td>
<td>2.7 [69]</td>
</tr>
<tr>
<td>Velocity ((\text{m/s}))</td>
<td>174</td>
<td>137</td>
<td>172</td>
</tr>
<tr>
<td>Time ((\mu \text{s}))</td>
<td>582</td>
<td>749</td>
<td>603</td>
</tr>
<tr>
<td>Strain rate ((\text{s}^{-1}))</td>
<td>593</td>
<td>469</td>
<td>592</td>
</tr>
<tr>
<td>Average True Flow Stress ((\text{MPa}))</td>
<td>406</td>
<td>280</td>
<td>115</td>
</tr>
</tbody>
</table>

Table 5.1: Estimation of metal velocities and strain rates at high rates.
The parameters used in the calculations and the estimated metal velocities and strain rates for each of the metal systems studied in this work are listed in Table 5.1. Average true flow stress has also been calculated for each of the metals as follows, which will be used in later calculations.

\[
\text{Plastic Work/unit volume} = \int_{\varepsilon_0}^{\varepsilon} \sigma \, d\varepsilon
\]

5.1.2 Hudson's equation:

Hudson [70] developed an analytical expression for the velocity of metal diaphragm formed in under-water explosion. It is shown in equation 6. He related the sample's maximum velocity, \( V_m \) to its free formed deflection, \( \Delta \). Strain hardening was neglected in his approach and other simplifying assumptions were also made.

\[
V_m = \frac{\Delta}{r} \sqrt{\frac{g\sigma_0}{\rho}} \tag{5.6}
\]

In the above expression, \( r \) is the radius of the clamped circular sample, \( \rho \) is the density of the sample, \( g \) is the acceleration due to gravity and \( \sigma_0 \) is the average material strength. If \( \sigma_0 \) is in SI units (e.g., Pascals), the "g" will be absent from the above expression. The average material strength was not very closely defined by Hudson. For the materials used in this investigation, the engineering quantity of average flow stress calculated earlier was used to arrive at velocity estimates using Hudson's equation. The Hudson's velocity estimate was 197 m/s for IF Iron, 153 m/s for Copper and 196 m/s for Aluminum. These are very close to the energy balance estimates shown
earlier. It must be noted that Hudson's equation assumes free forming of sheet metal.

5.1.3 Estimates from inertial shearing:
It may be recalled that the conical die used in the forming experiments was drilled with small holes of 1.6 mm diameter on opposite sides of the curved conical surface at various heights for mounting IRED-PT pair for velocity measurement. The holes were found punched out at high rate, but not at low rates. This gave another opportunity to estimate the metal velocity.

Let the diameter of the hole be D. It is known that during high rate blanking [71], a shear plug is formed first as shown in Figure 5.2, which later passes through the thickness of the sheet.

![Diagram of blanking mechanism](image)

Figure 5.2 Mechanism of blanking at high rates
If $E_{\text{shear}}$ is the energy required to shear the hole,

$$E_{\text{shear}} = \int_{x=0}^{t} F_{\text{max}} (t - x) \, dx \ldots \quad (5.7)$$

$$F_{\text{max}} = \tau \pi D \ t \ldots \quad (5.8)$$

This leads to

$$E_{\text{shear}} = \frac{\tau \pi D \ t^2}{2} \ldots \quad (5.9)$$

Equating this shear energy to the kinetic energy of the slug yields the velocity of the slug, which indicates the metal velocity at the location.

$$E_{\text{kinetic}} = \frac{1}{2} m \ V^2 = \frac{1}{2} \rho \pi \left(\frac{D}{2}\right)^2 \ t \ V^2 \quad (5.10)$$

$$V = \sqrt{\frac{4 \tau t}{\rho D}} = \sqrt{\frac{4 \bar{\sigma} t}{\rho \sqrt{3} D}} \quad (5.11)$$

where $\bar{\sigma}$ is the average flow stress of the material. Using the average flow stress calculated earlier, the metal velocities estimated in this manner were 189 m/s for copper and 314 m/s for Aluminum. The IF iron samples were formed prior to drilling these holes in the die. Assuming that the holes would have been punched out if the die used for IF iron also had the holes, the velocity estimate turns out to be 345 m/s. These estimates are not very far from earlier estimates. Summary of all these velocity estimates for the materials used in the current investigation is shown in Table 5.2.

There are however some important differences among the various estimates of velocities listed in Table 5.2. The energy balance and Hudson's method
provide the lower bound of the initial velocity, assuming that the final velocity at the completion of forming is zero. The inertial shearing method estimates the velocity of impact. The initial velocity of the metal will be higher than this value and thus it provides the upper bound of the estimate.

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy Balance Velocity (m/s)</th>
<th>Hudson's Eqn.[70] Velocity (m/s)</th>
<th>Inertial Shearing Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF Iron</td>
<td>174</td>
<td>197</td>
<td>345</td>
</tr>
<tr>
<td>OFHC Copper</td>
<td>137</td>
<td>153</td>
<td>189</td>
</tr>
<tr>
<td>6061 T4 Aluminum</td>
<td>172</td>
<td>196</td>
<td>314</td>
</tr>
</tbody>
</table>

Table 5.2: Estimates of high rate velocities on materials used in the current investigation.

5.1.4 Other velocity estimates from the literature:
Tobe et al. [15] measured the impulse of the shock wave and total time required for forming to be completed. For a discharge energy of 0.85 kJ, a circular metal sheet of 50 mm radius and 1 mm in thickness deformed to a central deflection of 17 mm. From the duration of impulse, the time required to form the sheet was estimated to be 0.7 ms. Material used was 99% pure aluminum annealed at 300°C for one hour. Material had a density of 2710 kg/m³. Tobe et al. [15] reported that the material had a Hollomon strength coefficient of 10.5 kgf/mm² and a strain hardening exponent of 0.24. With
the above parameters, Hudson's equation would predict a velocity of 49 m/s. Energy balance estimate gave 48 m/s.

Since the time required to form the sheet as well as the central deflection are known, the average velocity can also be measured in another way. Assuming that the velocity decreased linearly from the maximum value at the start of the forming to zero towards the end of forming,

\[ V = \frac{2 \Delta}{t} = 49 \text{ m/s} \]

This shows that both Energy balance estimate as well as Hudson's equation appear to be quite effective in predicting the metal velocity in high rate forming.

Sheet metal velocity has been measured by other researchers as well. Previous work on electrohydraulic forming shows that the sheet metal is typically accelerated to speeds in the range of 50 m/s to 300 m/s [20] and the strain rate has been estimated to be near 10^3 s^{-1} [15,20] under typical conditions. Kegg and Kulpakioglu [14] used a 5000 frames/sec high speed camera and observed that metal velocity in tube bulging was 76.2 m/s. Strain rate was 3000 s^{-1}. The material used was Aluminum and their system consisted of 25 kV voltage and seven capacitors of 1.5 \mu F each. Discharge was accomplished by spring driven closing of air gap.
5.2 Modeling of inertial effects:

In this section a simple and relatively intuitive model of a one dimensional high rate tensile test is presented. It shows that inertial forces should improve ductility, and estimates the workpiece velocities necessary to induce such an effect. An appropriate one-dimensional model should be able to capture the salient features of localization and ductility because final rupture almost always takes place in plane strain.

![Diagram](image)

Figure 5.3. Schematic description of the evolution of a simple tension test. Up to the point of maximum load, deformation is stable. Once localization is severe, there may be a sharp discontinuity in the velocity-position relation.
To start, it is well accepted and commonly observed that up to the point of maximum load, deformation within a tensile sample is uniform. As a result, in uniform deformation, the local velocity of a point on the sample varies linearly with position as shown in Figure 5.3. After the point of maximum load, in order for deformation to localize, the sample must meet a new velocity-position profile which may eventually approximate a step function. The change from the stable to the localized velocity profile takes place over some time period $\Delta t$. This change in velocity over time (acceleration) produces non-uniform inertial forces in the sample.

![Diagram](a)

![Diagram](c)

![Diagram](b)

![Diagram](d)

Figure 5.4. Right hand side of the sample introduced in Figure 5.3 with associated velocity and force profiles. The inertial force is not present in quasi-static deformation and tends to increase the stress in the perfect part of the sample.
Figure 5.4 shows the right hand side of the sample introduced in Figure 5.3, and we will let the center of the sample be the origin of the position \(x\) coordinate system and define velocity as zero at this location. In going from the stable state to the localized velocity profile, each location of the sample must go through a velocity change which is approximately shown in Figure 5.4(b).

\[
V_{\text{stable}} = \frac{V}{2} \left( 1 + \frac{x}{L} \right) \quad (5.12)
\]

Since \(V_{\text{localized}} = V\),

\[
\Delta v = \frac{V}{2} \left( 1 - \frac{x}{L} \right) \quad (5.13)
\]

Where \(\Delta v\) is the local change in velocity, \(V\) is the velocity at the sample end. For an infinitesimal strip, volume = \((b) \ (w) \ (dx)\) and mass = \(\rho bw \ dx\), where \(b\) and \(w\) are the sample thickness and width, \(\rho\) is the material density and \(L\) is the half-length of the sample. The inertial force at each location can be calculated by Newton’s law, where acceleration is estimated as the change in velocity, \(\Delta v\), divided by the time period between the end of stable flow and localization \(\Delta t\). The total inertial force, \(F_{\text{in}}\), transmitted through the sample can be written as:

\[
F_{\text{inertial}} = \int_{0}^{L} \rho bw \frac{\Delta v}{\Delta t} \ dx = \frac{\rho bwV}{2} \int_{0}^{L} \left( 1 - \frac{x}{L} \right) \ dx \quad (5.14)
\]

The maximum value of the inertial force is at the gripped end and has a value of:

\[
F_{\text{in}}^{\max} = \frac{\rho bwV}{2} \left( \frac{L}{2} \right) \quad (5.15)
\]

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This inertial force is tensile and would not be present in quasi-static deformation. It opposes the force at the gripped sample end and reduces the force available to stretch the sample. At any location, the force acting through the cross section is reduced by the inertial force. This tends to unload the portion of the sample that is localizing. This increases the stress and the amount of deformation in the ‘perfect’ part of the sample.

The time period in inducing localization, $\Delta t$, can be estimated by first recognizing that by similitude, the strain between load maximum and severe instability ($e_{loc}$ in Figure 5.3) is not a function of sample size for quasi-static tests.

The value is denoted as $e_{loc}^{static}$. The total elongation, $\Delta l$ consists only of $e_{loc}^{static}$, since additional elongation due to inertia is negligible.

Therefore,

$$\Delta t = \frac{\Delta l}{dx/dt} = \frac{e_{loc}^{static} L}{V}$$

(5.16)

Thus, the maximum increase in stress, which exists at the gripped end, can be re-written as:

$$F_{in}^{max} = \frac{V^2 \, bw \rho}{4 \, e_{loc}^{static}}$$

(5.17)

This can be rewritten as,

$$\Delta \sigma = \frac{F_{in}^{max}}{bw} = \frac{V^2 \, \rho}{4 \, e_{loc}^{static}}$$

(5.18)

It is proposed that additional elongation due to inertia becomes significant when the workpiece stress increases a given fraction, $f_1$.  

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Thus, \( \Delta \sigma = f_1 \sigma_0 = \frac{V^2 \rho}{4 e_{loc}^{\text{static}}} \) \hspace{1cm} (5.19)

A reasonable value for \( f_1 \) may be between 0.01 and 0.1. Using this, \( V_{\text{crit}} \) can then be expressed as:

\[
V_{\text{crit}} = \sqrt{\frac{4 f_1 e_{loc}^{\text{static}} \sigma_0}{\rho}} \hspace{1cm} (5.20)
\]

It is interesting to note here that it is the cross head velocity, rather than material strain rate that is important in determining if there will be increased formability due to inertial effects. This distinguishes this effect from changes in the material's constitutive law, which would be expected to scale with strain rate. Again, the origin of the effect is that the inertial forces act to diffuse deformation throughout the sample by increasing the stress at the gripped end.

The driving force for this may be seen as the neck being diffused by sample's acquisition of additional kinetic energy in the time period between load maximum and final localization. Hence, one may approach this problem from another angle by proposing that on purely dimensional grounds that it seems reasonable that this change in kinetic energy should scale with the amount of additional energy consumed in plastic deformation in high velocity deformation. Or stating this quantitatively, where \( E_{\text{kin}} \) is the kinetic energy the sample acquires during localization, and \( E_{\text{plast}} \) is the extra amount of plastic work done when inertial forces increase ductility, It is proposed that:

\[
E_{\text{plast}} = f_2 E_{\text{kin}} \hspace{1cm} (5.21)
\]
where $f_2$ is a scaling factor that relates these terms to one another. A reasonable value for this may be on the order of unity.

$$E_{kin} = F_{in}^{max} \left( L \ e_{loc}^{static} \right) = \frac{V^2 b w p L}{4}$$  \hspace{1cm} (5.22)

$$E_{plastic} = e_{ex} \ \sigma_0 \ bwL$$ \hspace{1cm} (5.23)

By relating these energy terms the extra increment in plastic sample extension $e_{ex}$ can be estimated as:

$$e_{ex} = \frac{f_2 V^2 p}{4 \sigma_0}$$ \hspace{1cm} (5.24)

Hu et al. [72] carried out a series of one dimensional numerical simulations of tensile test over a range of test velocities for materials having a Hollomon type constitutive behavior and power law strain rate sensitivity. One such simulation for material properties close to that of Iron used in the current forming experiments is shown in Figure 5.5. As the test velocity was increased, the total elongation remained the same up to a critical velocity. Beyond a critical velocity, the total elongation increased with increasing test velocity. The von Kármán critical velocity did not intervene, since the test was ring expansion.

Hu et al. [72] defined the critical velocity as the one at which there was at least 1% increase in total elongation. The critical velocity decreased with increase in strain hardening exponent (n) and decrease in strain rate sensitivity coefficient (m). The critical velocity was found to decrease with increasing
normalized material density, which was defined as the ratio of the density of the material to the Hollomon strength coefficient (K). Such a critical velocity for the onset of inertial effect was calculated [72] for many commonly used metals and are shown in Figure 5.6. This critical velocity is referred to in the figure as $V_c1$.

Figure 5.5 Engineering stress-strain curves at different test velocities in a simulated ring expansion test (Data from Ref. 72). The dimensionless engineering stress is the ratio of engineering stress to the strength coefficient in the Hollomon Law.
Figure 5.6 Critical velocity for the onset of inertial effect for some metals and alloys (Data from Ref. 72). Open symbols indicate that $m$ was assumed to be zero. Closed points indicate that actual $m$ values of the material were used.

The simple analytical model described above captures many of the significant features shown in the more comprehensive one-dimensional finite element modeling performed by Hu et al. [72], which includes both rate-sensitivity and strain hardening. Specifically, both models show that inertia induced excess
elongation becomes appreciable only after a critical velocity. Both models predict similar values for the critical velocity and that the change in ductility with velocity is stronger than linear as shown in Figure 5.7. However, the present analytical model has a much stronger variation in elongation with velocity than that of Hu et al. [72].

![Graph showing comparison between Hu et al. model and analytical model](image)

**Figure 5.7** Comparison of the analytical model with the numerical simulation data from Ref. 72.

Hu [73, 74] modified the above equations for critical velocity as follows:

Recall the equation derived earlier for the maximum inertial force,

\[
F_{\text{in}}^{\text{max}} = \frac{\rho bwV}{2 \Delta t} \left( \frac{L}{2} \right)
\]

(5.15)
This maximum inertial force leads to increase of engineering stress, \( s \), which exists at the gripped end.

\[
\Delta s = \frac{F_{in}}{b \omega} = \frac{V\rho L}{2\Delta t} \tag{5.25}
\]

If \( e_u^{static} \) is the uniform strain in uniaxial tension at low rate, then the static elongation is \( 2 L e_T^{static} \). The time interval required to produce an additional elongation of 1\% of static elongation can be expressed as:

\[
\Delta t = \frac{0.02 \ L}{V} \frac{e_u^{static}}{\Delta s} \tag{5.26}
\]

Substituting this expression in the expression for \( \Delta s \) yields the expression for \( V_{critical} \) as:

\[
V_{critical} = \sqrt{\frac{0.04 \ e_u^{static} \Delta s}{\rho}} \tag{5.27}
\]

If the material follows Hollomon law, \( \sigma = K \ e^n \),

\[
e_u^{static} = ln \ (1 + e_u^{static}) = n \tag{5.28}
\]

Hence,

\[
e_u^{static} = exp(n) - 1 \tag{5.29}
\]

If \( \Delta \sigma \) is the increase in true stress,

\[
\Delta \sigma = K \left[ (e_u + e_{in})^n - e_u^n \right] \tag{5.30}
\]

where \( e_{in} \) is the increase in true strain due to inertia at the critical velocity and by definition earlier, is equal to 0.01 \( e_u = 0.01 \ n \).

Therefore,

\[
\Delta \sigma = K \left[ (1.01 \ n)^n - n^n \right] \tag{5.31}
\]
Since the increase in strain is small, this increase in true stress can be assumed to be the same as increase in engineering stress $\Delta s$.

Then the expression for $V_{\text{critical}}$ can be re-written as,

$$V_{\text{critical}} = \sqrt{\frac{0.04 \ K \ [\exp(n) - 1] \ [1.01 \ n]^n - n^n}{\rho}}$$ (5.32)

Using the above expression, the critical velocity for all of the materials used in the current investigation were calculated and these are shown in Table 5.3. The quantity $\sigma_0$, which is the true stress corresponding to the maximum uniform elongation in a static test is also known. Assuming the maximum value of unity for $f_2$, the excess elongation due to inertia predicted by this model can be calculated for each of the materials used in the experiments.

These are also shown in Table 5.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>$K$ (MPa)</th>
<th>$n$</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$V_{\text{critical}}$ (m/s)</th>
<th>$\Delta\sigma$ (MPa)</th>
<th>$\sigma_0$ (MPa)</th>
<th>$e_{\text{ex}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF Iron</td>
<td>544</td>
<td>0.236</td>
<td>7800</td>
<td>1.12</td>
<td>0.9096</td>
<td>386.91</td>
<td>0.153</td>
</tr>
<tr>
<td>OFHC Copper</td>
<td>365</td>
<td>0.217</td>
<td>8920</td>
<td>0.78</td>
<td>0.5663</td>
<td>262.00</td>
<td>0.160</td>
</tr>
<tr>
<td>6061 T4 Aluminum</td>
<td>176</td>
<td>0.230</td>
<td>2700</td>
<td>1.05</td>
<td>0.2876</td>
<td>125.52</td>
<td>0.160</td>
</tr>
</tbody>
</table>

Table 5.3: Critical velocities for materials used in the experiments to exhibit inertial effects:
It is apparent from Table 5.3 that for the estimated velocities at high rates, the proposed analytical model could predict an increase in uniaxial strain of 0.15 to 0.16.

5.3 Experimental support for inertia:
It is apparent from the above estimates of energies and time scales that they are appropriate for inertial effects to be large. The estimated sample velocities always exceeded the calculated critical velocity for stabilizing localization. A small circular piece (2 cm in diameter) of IF iron sheet was lightly taped to the bottom of the flat IF iron sheet and formed in electrohydraulic forming. After the forming, the sheet was found to conform to the shape of the bigger sample. Under quasi-static conditions there would be essentially no stress on the small piece and it would have fallen off within a few seconds of forming. In this case, the disc's own momentum provided all the energy for its forming. This shows that inertial effects are substantial and should be considered in any formability analysis of the process.

5.4 Von Kármán limit velocity:
When the workpiece velocity is increased in uniaxial tensile test, a limit velocity is reached, called Von Kármán velocity [51]. Beyond this critical velocity, the plastic strain can not be propagated through the specimen as fast as its mobile end. As a result, fracture occurs very near the mobile end. Consequently, one may encounter a total elongation much lower than that obtained at conventional (lower) velocities, even though the fracture is not completely brittle. Von Kármán proposed the following equation for the
velocity of plastic wave propagation in a tensile specimen, \( C_P \) assuming rate independent material behavior,

\[
C_P = \sqrt{\frac{1}{\rho} \left( \frac{ds}{de} \right)}
\]  

(5.33)

where \( ds/\text{de} \) is the slope of the engineering stress-strain curve. The equation shows that each increment of plastic strain propagates at a different velocity. Since \( ds/\text{de} \) depends on the magnitude of the plastic strain, the shape of the wave changes as it propagates along the specimen. The velocity of propagation of the plastic strain varies from zero to the elastic wave velocity, depending upon the strain amplitude, but most plastic strains propagate at roughly one-tenth of the elastic wave velocity. The material velocity related to the wave velocity at any given elongation, \( e \), is written as:

\[
v = \int_0^e C_P \, \text{de} = \sqrt{\frac{1}{\rho}} \int_0^e \sqrt{\frac{\text{ds}}{\text{de}}} \, \text{de}
\]  

(5.34)

Integrating the above equation from zero to uniform strain gives the maximum material velocity corresponding to a tensile elongation at which \( ds/\text{de} \) is zero. If Hollomon behavior is assumed for the material, the above equation can be re-written as,

\[
V_{c2} = v = \sqrt{\frac{1}{\rho_n}} \int_0^n \sqrt{(n - \varepsilon)} \varepsilon^{(n-1)/2} \, \text{d}\varepsilon
\]  

(5.35)

This von Kármán's velocity, termed as second critical velocity, \( V_{c2} \) in the current high rate experiments, can be computed using numerical integration. These have been shown in Figure 5.8.
Figure 5.8 Calculated von Kármán critical velocity for various materials. Data from Hu and Daehn (74).

The critical velocity $V_{C1}$ required for inertial effects varied from 0.1 to 5 m/s whereas von Kármán velocities varied from 30 to 200 m/s for various materials. These data indicate that there appears to be a window of velocity regime existing for any material, where one can expect inertial effects to be appreciable without worrying about von Kármán localization effect. The
above analysis provides a reasonable estimates of such velocity regimes. Specifically, the von Kármán velocity estimates can be construed as the minimum estimates, since rate independent behavior was assumed by von Kármán.

5.5 Proposed inertial ironing effect:
Even though the one dimensional analytical model could successfully incorporate inertia effects and predict increase in uniaxial strain, the actual improvement observed in biaxial formability was much more dramatic. Changes in fundamental constitutive behavior of material did not appear to take place, since the terminal hardness was lower than the corresponding hardesses at low rates for IF iron. Even in the case of Aluminum and Copper, though the hardness was higher at high rates, it was within 20% of corresponding hardness in low rate sample at all values of strain. Hence, formability improvement due to changes in fundamental material constitutive behavior appears unlikely.

Another contributing factor to the biaxial formability improvement could come from the compressive stress generated by the impact of the sheet metal on the female die. When the sheet metal strikes the rigid wall of the conical die at velocities of a few hundred meters per second, it is decelerated rapidly as shown in Figure 5.9.

Let us assume that the sheet metal decelerates over a distance \( x_d \). If \( V_0 \) is the metal velocity before it strikes the die, the deceleration is given by
\[ a = \frac{V_0^2}{2} x_d \] (5.36)

The accompanying compressive force, \( F_c \) and stress \( \sigma_c \) are given by,

\[ F_c = ma = \rho \; dx \; dy \; t \left( \frac{V_0^2}{2x_d} \right) \] (5.37)

\[ \sigma_c = \frac{F}{dx \; dy} = \rho \; t \; \frac{V_0^2}{2} x_d \] (5.38)

This compressive stress could be appreciable compared to the average flow stress if the deceleration is assumed to take place over 1 mm distance as shown in Table 5.4.

![Figure 5.9 Inertial ironing effect in high rate forming](image)

The average stress shown in the table was calculated by taking the ratio of plastic work per unit volume from Table 5.1 and dividing it by the effective strain also shown in Table 5.1. The ironing stress was calculated from equation 5.38. This wall ironing force is also inertially driven, since it is
higher for heavier and thicker materials. The effect of such a force can be likened to rolling. This ironing force is compressive in nature and it contributes to stretching of the sheet metal instead of localization. From Table 5.4, it clear that this inertial ironing force could be as much as 50% of average flow stress in some cases.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Thickness (mm)</th>
<th>Velocity (m/s)</th>
<th>Av. stress (MPa)</th>
<th>Ironing Stress (MPa) from eqn. 5.38</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF Iron</td>
<td>7800</td>
<td>0.84</td>
<td>174</td>
<td>406</td>
<td>99</td>
</tr>
<tr>
<td>OFHC Copper</td>
<td>8920</td>
<td>0.79</td>
<td>137</td>
<td>280</td>
<td>66</td>
</tr>
<tr>
<td>6061 T4 Aluminum</td>
<td>2700</td>
<td>1.60</td>
<td>172</td>
<td>115</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 5.4: Estimates of wall ironing compressive stress at the die wall on materials formed at high rates.

5.6 Experimental verification of inertial ironing effect:
This inertial ironing effect can be verified by formability studies at high rates, on identical materials differing only in thickness. Copper sheets of thickness 0.34 mm (referred to as thin copper) and 0.79 mm (referred to as thick copper) were studied for formability at high rates. The thick copper sheet filled the die completely at 20 kJ of discharge energy. On the thin copper sheet, no significant in formability could be seen when using up to 8 kJ of discharge energy as shown in Figure 5.10. Energies above 8 kJ caused large segments to
be torn out of the center of the sample as shown in Figure 5.11. Despite various attempts, no optimum discharge energy could be found for the thin copper sheet to fill the conical die completely at high rates. It is postulated that inertial ironing effect was not significant enough in the case of thin copper.

![Image](image_url)

Figure 5.10 Thin (0.34 mm) copper sheet formed at low rate (left) and high rate (right). Discharge Energy at high rate: 7.75 kJ.

In order to verify the inertial ironing effect further, the thin and thick copper sheets were clamped together and formed at high rates. When the thin copper was placed on top of the thick copper and formed, both the sheet could fill the conical die completely at a discharge energy of 25 kJ. When the order was reversed with thin copper on the bottom and the thick copper sheet on top, only the thick copper sheet could get to fill the die completely. The thin copper sheet tore in the middle just as it did earlier when formed separately. These are shown in Figure 5.12. The discharge energy required was only 21 kJ
in this case. When the discharge energy was increased further, the thin copper sheet only tore more and could never get to fill the die.

Figure 5.11 Thin (0.34 mm) copper sheet formed at low rate (left) and high rate (right) using a higher energy. Discharge Energy: 8 kJ. Notice the large segments torn out at the center of the sample at high rate.

Figure 5.12 High rate samples showing the inertial ironing effect. (a) Low rate sample. (b) With thin sheet on top of thick sheet, both the sheets filled the die. Discharge energy: 25 kJ. (c) With the order reversed, only the thick sheet filled the die. Energy: 21 kJ.
Recall that when these two sheets were formed individually, the thick copper could be formed successfully at high rate, but not the thin sheet. When the thin sheet was on top, the thick copper sheet beneath it provided the necessary momentum for the inertial ironing force. The ironing force acted dominantly on the thin copper sheet and enhanced its formability. The thick sheet also filled the die, as it did when formed individually. When the order was reversed, the ironing force acted dominantly on the thick sheet since it was closer to the die. In the absence of inertial ironing force, the thin copper sheet tore as it did when formed individually earlier.

5.7 Estimate of adiabatic temperature rise:

High metal velocities that exist at in high rate forming processes are also generally accompanied by high strain rates. When strain rates are high, non-isothermal effects such as adiabatic localization can intervene producing lower instability strains as explained before. Hence, it is important to estimate approximately the possible adiabatic temperature rise at high rates. The following procedure was adopted to estimate the adiabatic temperature rise in the samples formed at high strain rate.

A small element on the sheet sample is considered. For simplicity, this was chosen to be one circle in the grid pattern. This circle of diameter $d_0$ changed to the shape of an ellipse after forming from which the three dimensional strain is calculated. A rate independent Hollomon law was assumed for all the three materials used in the current investigation. The total plastic work per unit volume done on that element is given by,
\[ W = \int_{0}^{\varepsilon_t} \sigma \, d\bar{e} = \frac{K}{n+1} \left[ \varepsilon^{n+1} \right]_{0}^{\varepsilon_t} \]  

(5.39)

In the above expression, typically the tresca effective strain can be used. The heat generated over the grid circle area is given by:

\[ H = \rho \, C_p \, \Delta T \]  

(5.40)

Where \( C_p \) is the heat capacity of the material, \( \rho \) its density and \( \Delta T \) the adiabatic temperature increase. Assuming that the entire plastic work is converted to heat gives us an idea of maximum possible adiabatic temperature increase, as given by the following equation.

\[ \Delta T = \frac{K \, \varepsilon_t^{n+1}}{\rho C_p (n+1)} \]  

(5.41)

Extending this analysis, one can compute temperature increase in various circular elements along the curved surface area of the cone, which will give adiabatic temperature increase along that surface. Known values of material density, total strain and strength coefficients for each of the three materials were used. Heat capacity values used were 464 J/kg °K [67] for IF iron, 393 J/kg°K [68] for Copper and 913 J/kg°K [75] for 6061 T4 Aluminum. The corresponding expressions for \( \Delta T \) in °C for each of these materials are:

**IF Iron:**  
\[ \Delta T = \left( \frac{544 \times 10^6}{7800 \times 464 \times 1.236} \right) \varepsilon_t^{1.236} = 121.610 \varepsilon_t^{1.236} \]  

(5.42)

**Copper:**  
\[ \Delta T = \left( \frac{365 \times 10^6}{8920 \times 393 \times 1.217} \right) \varepsilon_t^{1.217} = 85.555 \varepsilon_t^{1.217} \]  

(5.43)

**Aluminum:**  
\[ \Delta T = \left( \frac{176 \times 10^6}{2700 \times 913 \times 1.23} \right) \varepsilon_t^{1.23} = 58.046 \varepsilon_t^{1.23} \]  

(5.44)
The $\varepsilon_t$ used in the above expressions were Tresca effective strain, which was most often the magnitude of the thickness strain, but not always so, as shown in Tables 5.5 to 5.7. The temperature profiles for IF iron, Copper and 6061 T4 Aluminum are shown in Figures 5.13 to 5.15. The strain measurements were made on every circle of grid along a line of circle from the edge of the conical shape to the apex. Circle No. 0 indicates the edge and the highest circle No. in the tables and figures indicates apex.

Figure 5.13 Variation of thickness strain and estimated adiabatic temperature rise for IF Iron. Distance is along the curved surface of the cone formed at high rates. (Distance indicated in the form of circle No. from the foot of the cone).
<table>
<thead>
<tr>
<th>Circle No.</th>
<th>True minor strain</th>
<th>True major strain</th>
<th>Tresca effective strain</th>
<th>ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.168</td>
<td>0.752</td>
<td>0.920</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>0.181</td>
<td>0.724</td>
<td>0.905</td>
<td>107</td>
</tr>
<tr>
<td>3</td>
<td>0.011</td>
<td>0.695</td>
<td>0.706</td>
<td>79</td>
</tr>
<tr>
<td>4</td>
<td>0.087</td>
<td>0.667</td>
<td>0.754</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>0.123</td>
<td>0.649</td>
<td>0.771</td>
<td>88</td>
</tr>
<tr>
<td>6</td>
<td>-0.134</td>
<td>0.858</td>
<td>0.858</td>
<td>101</td>
</tr>
<tr>
<td>7</td>
<td>-0.037</td>
<td>0.878</td>
<td>0.878</td>
<td>104</td>
</tr>
<tr>
<td>8</td>
<td>0.058</td>
<td>0.938</td>
<td>0.997</td>
<td>121</td>
</tr>
<tr>
<td>9</td>
<td>0.143</td>
<td>0.714</td>
<td>0.857</td>
<td>101</td>
</tr>
<tr>
<td>10</td>
<td>-0.084</td>
<td>0.953</td>
<td>0.953</td>
<td>115</td>
</tr>
<tr>
<td>11</td>
<td>-0.007</td>
<td>0.770</td>
<td>0.770</td>
<td>88</td>
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<tr>
<td>12</td>
<td>0.075</td>
<td>0.832</td>
<td>0.907</td>
<td>108</td>
</tr>
<tr>
<td>13</td>
<td>-0.077</td>
<td>0.831</td>
<td>0.831</td>
<td>97</td>
</tr>
<tr>
<td>14</td>
<td>0.012</td>
<td>0.711</td>
<td>0.722</td>
<td>81</td>
</tr>
<tr>
<td>15</td>
<td>0.012</td>
<td>0.755</td>
<td>0.766</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 5.5: Strain distribution and estimated adiabatic temperature rise along the curved surface of IF Iron sample formed at high rate.
<table>
<thead>
<tr>
<th>Circle No.</th>
<th>True minor strain</th>
<th>True major strain</th>
<th>Tresca effective strain</th>
<th>ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.171</td>
<td>0.597</td>
<td>0.768</td>
<td>62</td>
</tr>
<tr>
<td>2</td>
<td>0.129</td>
<td>0.583</td>
<td>0.712</td>
<td>57</td>
</tr>
<tr>
<td>3</td>
<td>0.138</td>
<td>0.613</td>
<td>0.750</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>0.161</td>
<td>0.673</td>
<td>0.834</td>
<td>69</td>
</tr>
<tr>
<td>5</td>
<td>0.260</td>
<td>0.633</td>
<td>0.892</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>0.242</td>
<td>0.672</td>
<td>0.914</td>
<td>77</td>
</tr>
<tr>
<td>7</td>
<td>0.092</td>
<td>0.510</td>
<td>0.602</td>
<td>46</td>
</tr>
<tr>
<td>8</td>
<td>0.129</td>
<td>0.689</td>
<td>0.818</td>
<td>67</td>
</tr>
<tr>
<td>9</td>
<td>0.238</td>
<td>0.691</td>
<td>0.929</td>
<td>78</td>
</tr>
<tr>
<td>10</td>
<td>0.207</td>
<td>0.580</td>
<td>0.787</td>
<td>64</td>
</tr>
<tr>
<td>11</td>
<td>0.066</td>
<td>0.551</td>
<td>0.617</td>
<td>48</td>
</tr>
<tr>
<td>12</td>
<td>-0.014</td>
<td>0.526</td>
<td>0.526</td>
<td>39</td>
</tr>
<tr>
<td>13</td>
<td>0.039</td>
<td>0.505</td>
<td>0.544</td>
<td>41</td>
</tr>
<tr>
<td>14</td>
<td>-0.071</td>
<td>0.602</td>
<td>0.602</td>
<td>46</td>
</tr>
<tr>
<td>15</td>
<td>0.246</td>
<td>0.569</td>
<td>0.815</td>
<td>67</td>
</tr>
</tbody>
</table>

Table 5.6: Strain distribution and estimated adiabatic temperature rise along the curved surface of OFHC Copper sample formed at high rate.
Figure 5.14 Variation of true thickness strain and estimated adiabatic temperature rise for OFHC Copper. Distance is along the curved surface of the cone formed at high rates. (Distance indicated in the form of circle No. from the foot of the cone).
<table>
<thead>
<tr>
<th>Circle No.</th>
<th>True minor strain</th>
<th>True major strain</th>
<th>Tresca effective strain</th>
<th>ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.295</td>
<td>0.623</td>
<td>0.917</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>0.308</td>
<td>0.621</td>
<td>0.929</td>
<td>53</td>
</tr>
<tr>
<td>3</td>
<td>0.280</td>
<td>0.614</td>
<td>0.894</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>0.341</td>
<td>0.642</td>
<td>0.983</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>0.238</td>
<td>0.664</td>
<td>0.902</td>
<td>51</td>
</tr>
<tr>
<td>6</td>
<td>0.225</td>
<td>0.585</td>
<td>0.810</td>
<td>45</td>
</tr>
<tr>
<td>7</td>
<td>0.186</td>
<td>0.667</td>
<td>0.853</td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>0.186</td>
<td>0.634</td>
<td>0.820</td>
<td>45</td>
</tr>
<tr>
<td>9</td>
<td>0.158</td>
<td>0.702</td>
<td>0.860</td>
<td>48</td>
</tr>
<tr>
<td>10</td>
<td>0.169</td>
<td>0.832</td>
<td>1.000</td>
<td>58</td>
</tr>
<tr>
<td>11</td>
<td>0.131</td>
<td>0.825</td>
<td>0.956</td>
<td>55</td>
</tr>
<tr>
<td>12</td>
<td>0.190</td>
<td>0.647</td>
<td>0.836</td>
<td>47</td>
</tr>
<tr>
<td>13</td>
<td>0.196</td>
<td>0.543</td>
<td>0.739</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>0.030</td>
<td>0.798</td>
<td>0.828</td>
<td>46</td>
</tr>
<tr>
<td>15</td>
<td>0.071</td>
<td>0.846</td>
<td>0.917</td>
<td>52</td>
</tr>
<tr>
<td>16</td>
<td>0.060</td>
<td>0.668</td>
<td>0.728</td>
<td>39</td>
</tr>
<tr>
<td>17</td>
<td>0.061</td>
<td>0.719</td>
<td>0.779</td>
<td>43</td>
</tr>
<tr>
<td>18</td>
<td>0.099</td>
<td>0.816</td>
<td>0.915</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 5.7: Strain distribution and estimated adiabatic temperature rise along the curved surface of 6061 T4 Aluminum sample formed at high rate.
Figure 5.15 Variation of thickness strain and estimated adiabatic temperature rise for 6061 T4 Aluminum. Distance is along the curved surface of the cone formed at high rates. (Distance indicated in the form of circle No. from the foot of the cone).

It is clear from the above estimates that adiabatic temperature increases are small and are thus not a major concern in the strain rate regime encountered in the current investigation.

It has been shown that the experimentally observed increase in formability can be successfully modeled. A simple one dimensional analytical model incorporating inertial effects is able to capture part of this increased
formability. Additionally, there appears to be a compressive inertial ironing force developed when the sheet impacts the die. It has been shown both analytically as well as experimentally that if this compressive force is appreciable, significant contribution to formability improvement can be expected. The metal velocities encountered in such high rate forming process appears to be still lower than Von Kármán critical velocity, hence localization is prevented. Also, localization due to adiabatic heating has been shown to be negligible.
CHAPTER VI

DISCUSSION

Experimental results have shown that common sheet metals such as IF Iron, OFHC Copper and 6061 T4 Aluminum could be stretched to fill a conical die completely when deformed at high rates while the same could not be achieved in the conventional forming. The principal strains measured on the samples were well in excess of 100%. When the measured in-plane strains were superimposed on the conventional Forming Limit Diagram, it appeared as though the forming limits were increased over 2 to 5 times the conventional limits.

6.1 Factors affecting shifts in Forming Limit Diagrams:
Forming Limit Diagram is considered to be not affected significantly by sheet thickness or strain rate in conventional sheet forming operations [64]. Gotoh [76] observed that for very thin sheets (of thickness below 0.1 mm), the limit strain decreases with decrease in sheet thickness. For very thick sheets, in-plane condition no longer holds good for stress-strain analysis. Hence Forming Limit concepts are preferably used in the intermediate thickness range. In such a range, various equations are suggested. Gotoh proposed theoretically the following equation:
\[
\left[ (\varepsilon_1)_{Cr} \right]_{\alpha=1}^* = \left[ (\varepsilon_1)_{Cr} \right]_{\alpha=1}^* \left[ 1 + \xi_1 \left\{ (t/t^*)^2 - 1 \right\} - \xi_2 \left\{ (t/t^*)^4 - 1 \right\} \right]
\]

where the limit strain for \( \alpha=1 \) (equi-biaxial tension) with a proportional loading is expressed. \( t^* \) is the representative thickness associated with the limit strain which is assumed to be known.

\[ \left[ (\varepsilon_1)_{Cr} \right]_{\alpha=1}^* \] is the limit strain at \( t^* \), and is known. \( \xi_1 \) and \( \xi_2 \) are constants.

Use of this equation requires determination of constants specific to the material system.

The Forming Limit Diagram for the Interstitial Free Iron used in the current investigation was constructed and provided by J. Siles [57] of Armco Iron. He proposed the following simpler equation for the variation of FLD_0 with thickness and strain hardening exponent.

FLD_0 = \( (n/0.21) \left( 23.3 + 359 \times t \right) \) where \( t \) is material thickness in inches and \( n \) is strain hardening exponent determined between 10% and 20% engineering strain.

Wilson [77] noted that when sheet thickness is reduced in rolling, the sizes of some of the plastic inhomogenieties in the microstructure are not reduced in proportion to the reduction in thickness of the sheet. Hence, reductions in sheet thickness may be expected to cause reductions in biaxial limit strains.

With regard to the effect of strain rate on the forming limits, Hecker [64] reported that the Forming Limits do not change appreciably with strain rates at conventional static strain rates.
The marginal 10% allowance provided in the forming limit diagrams can be expected to capture such small changes in material thickness, differences in inhomogenieties and small changes in strain rates. Increases observed in the current investigation are far greater than such small changes. It is thus important to understand all the issues involved that could affect formability at high rates.

6.2 Other factors affecting formability:
As mentioned earlier, formability of sheet metal may be affected at high velocity due to the following factors:
1. Inertial effects can increase sheet formability at high rates.
2. Inertial ironing produced by die-wall interaction can also increase sheet formability at high rates.
3. If von Kármán velocity is reached during a high rate metal forming, formability can actually be reduced and finally,
4. If adiabatic localization sets in, formability of sheet metal can actually be reduced.

It has been shown earlier in this investigation that the metal velocity and strain rates in this investigation are high enough for inertial effects and inertial ironing to be large, thus contributing to increased formability. It was also shown that von Kármán velocity was still high enough and was possibly not reached in this investigation, thus preventing premature failure. The strain rate was also not high enough to cause adiabatic localization to set in and interfere with the forming.
In addition to the above factors, there are other phenomena usually associated with high strain rate forming that could affect sheet formability.

6.2.1 Strain rate hardening:
Shock waves as such can cause significant changes in material properties. Shock stresses in solids typically range from tens of kilobars to megabars. Such stress levels are produced in a solid for duration of the order of several microseconds when an explosive is detonated in contact with it, when a projectile traveling at high velocity impacts on it, or when energy is deposited in it at very high power levels. Most solids deform irreversibly or fracture at stresses typically of the order of a few kilobars; thus, the generation and propagation of shock waves are intrinsically violent and destructive processes. This was evident in many of the shock studies.

ARMCO Iron shock formed at 50 GPa (at strain rate of $10^6$ s$^{-1}$) is reported to have shown a hardness of 200 HV compared to 82 HV on unshocked iron [78]. Copper has shown increase in yield strength from 210 MPa at 1.5% strain compared to 350 MPa at 26% strain when shock deformed at 10 GPa (at a velocity of 518 m/s) [79]. While such increases in hardness are fairly common, the mechanism behind such increase is not fully understood. Gray III [80] explained the commonly believed mechanism as follows: "In high rate deformation such as shock loading, the dislocation motion is believed to be restricted to the shear wave velocity material. Such subsonic restriction on dislocation motion leads to higher dislocation and point defect generation rates, resulting in enhanced hardening when compared to materials deformed to equivalent strains at quasi-static states." This view is shared by
other researchers as well [36]. Shock front that separates compressed material from that which is uncompressed is very abrupt; hence, the movement and generation of large numbers of dislocations is strongly enhanced. Terminal hardness can thus be related to peak shock stress experienced by the metal [81]. However, if the flow is rate dependent, then shock pulse duration may also affect terminal hardness. For example, if the material initially responds elastically until dislocation motion and generation can produce plastic strain, then the shear stresses acting on dislocations will be much greater than predicted by the rate-independent description. Subsequently they relax. Since relaxation time is involved, the degree of completion may be expected to be determined by the shock pulse duration [81]. An example of dissenting view to subsonic restriction of dislocation motion is the one by Gillis and Kelly [82]. "It is well known that on the basis of linear elastic theory, the energy of a dislocation line becomes infinite as its velocity approaches the shear wave velocity of the material, which would suggest that the dislocation velocity could not exceed this value. However the use of linear elasticity in association with the very high stress fields predicted at speeds close to the shear wave speed is highly questionable and many workers have taken the attitude that if driving forces are available, the dislocation will respond by moving at appropriate velocities which could include supersonic velocities."

These results from shock studies can be compared with the hardness results obtained in the current investigation to understand the mechanism behind formability improvement. In earlier discussions on the origins of increased plasticity, it was mentioned that increased rate of strain hardening could also cause improved formability at high rates. If the rate of strain hardening
increases at high velocities, the material can be expected to show dramatic increase in hardness at high velocities than those formed at low velocity for a given amount of strain. This increase could be substantial if the entire formability improvement is attributed to increased rate of strain hardening. In the case of IF iron (Figure 4.14), high strain rate sample showed lower hardness than the low strain rate sample for a given strain. This suggests that thermal softening may have dominated over any possible shock hardening of the material. Copper (Figure 4.15) and Aluminum (Figure 4.16) both exhibited slightly higher hardness at high strain rates at all values of strain. However, the difference in hardness between low and high rate samples at any given strain was always less than 20% and was therefore not so significant as to suggest shock hardening.

6.2.3 Strain path changes:
Changes in strain path is an important consideration in sheet forming operation. Semiatin and Jonas [83] pointed out that when strain path is changed, Bauschinger effect can occur. These are generally restricted to strain intervals of about 3% and can thus be termed transient effects. The behavior that follows a Bauschinger transient involves work softening as a result of strain path changes. This type of phenomenon is observed when an approximately axisymmetric strain path is followed by a period of plane strain deformation. Because the work hardening rate at a given equivalent strain (or stress) is higher during axisymmetric tension or compression than under plane strain conditions [84-87], a change in strain path from the former to the latter generally leads to a period of work softening, or to a temporary absence of work hardening. Under isothermal conditions, this does not lead to
significant macroscopic instabilities. However, when combined with adiabatic heating considerations, the decrease in work hardening rate that accompanies strain path changes can play a central role in the initiation and propagation of microscopic shear bands.

![Diagram](image)

Figure 6.1: Geometric position of sheet metal during the early stages of forming in a conical die.

Forming a sheet metal to a conical shape in a female die cavity has been analyzed by Ghosh and Hamilton [88]. When the sheet metal is deformed using a conical female die, the shape of the sheet in the initial stages of forming will be free bulging with no die interaction as shown in Figure 6.1. The radius of the spherical segment will vary with the height of the component formed. At some critical value of "h", the die wall will become tangential to the spherical portion as shown in Figure 6.2. The crown (uncontacted) region assumes a partial spherical shape [88]. The assumption
used in free bulging of a circular membrane are still used. In addition, Ghosh and Hamilton [88] also assumed that sticking (infinite) friction exists in the contacted region. Beyond this stage in the forming, the sheet will make contact with the die and take up an intermediate position as shown in Figure 6.5. Extending the simple analysis of Ghosh and Hamilton [88], analytical relations can be derived for each of these three distinct stages, from which average strain and strain rate can be estimated. The details are shown in the appendix.

Figure 6.2: Geometric position of sheet metal formed in a conical die when the sheet begins to make contact with the die wall.

Ghosh and Hamilton [88] pointed out that in circular bulge as well as forming in a conical die, the pole is in equibiaxial tension and the strain state changes toward plane strain near the edge (or the boundary between contacted and un contacted regions). The actual strain state may be different from their analysis depending upon the frictional conditions, but it is possible that strain
state might have changed continuously during the forming process. The resultant strain path changes could have led to decreased work hardening rate in IF iron and reduced the extent of work hardening in Copper and Aluminum. Since adiabatic conditions do exist at high strain rates, these strain path changes would have provided favorable conditions for initiation and propagation of microscopic shear bands. In that case the formability would have actually decreased and not increased as is observed in the current investigation. Hence either the strain path changes were not significant or the adiabatic temperature increase was not high enough to cause any premature failure in all of the three metals studied in the current investigation.

![Figure 6.3: Geometric position of a sheet metal during the later stage of forming in a conical die.](image)

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6.3. Comparison with superplasticity:
The dramatic increases in sheet formability that is seen in the current investigation parallels the one normally seen in superplastic forming. However, there are some major differences between the two processes. Importantly, the formability increase in superplastic forming is achieved by carefully engineering the microstructure and by a special forming in an optimum strain rate and temperature window. High strain rate sensitivity is responsible for dramatic increase in formability in superplastic forming. In electrohydraulic forming and related high rate processes, inertial effects have been shown to be responsible for the increase in formability. Also, there appears to be no change in material constitutive behavior that could be responsible for increase in formability. A more extensive comparison between superplastic forming and the high rate processes is shown in Table 6.1 and Table 6.2. Since the current effect is so different from superplasticity in many respects, it is named "hyperplasticity," in order to encourage further study in this area.
<table>
<thead>
<tr>
<th>Superplastic Forming</th>
<th>Hyperplastic Forming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requires one sided die and thus reduces tool cost.</td>
<td>Shock waves fill in the role of one of the dies and thus one sided die is required.</td>
</tr>
<tr>
<td>Spring back is known to less than in conventional processes.</td>
<td>Though not studied in depth, spring back has been widely observed to be almost non-existent [1,3,10,12,20].</td>
</tr>
<tr>
<td>Has the ability to produce complex shapes with intricate surface detail.</td>
<td>Complex shapes have been produced with excellent reproduction of surface detail.</td>
</tr>
</tbody>
</table>

Table 6.1: Similarities between superplastic and hyperplastic forming.
<table>
<thead>
<tr>
<th>Superplastic Forming</th>
<th>Hyperplastic Forming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superplastic forming is done isothermally at controlled temperature.</td>
<td>This process can be done at ambient temperature.</td>
</tr>
<tr>
<td>Material has to be specially prepared before the forming process.</td>
<td>Any material can be a candidate for this process. No special pre-processing is required.</td>
</tr>
<tr>
<td>Changes in the material constitutive behavior occurs.</td>
<td>Material constitutive behavior does not change appreciably. Terminal hardness does not increase appreciably. Thus subsequent operations can be directly performed.</td>
</tr>
<tr>
<td>High strain rate sensitivity slows the neck growth in superplastic forming thus increasing the formability.</td>
<td>Inertial forces slow the neck growth resulting in increased formability.</td>
</tr>
<tr>
<td>Process has been well studied in the last 20 years.</td>
<td>Related processes have been almost ignored in the last 20 years.</td>
</tr>
<tr>
<td>Amenable to low production rates with little capital.</td>
<td>High production rates are possible, but significant capital is required.</td>
</tr>
</tbody>
</table>

Table 6.2: Differences between superplastic forming and hyperplastic forming.
6.4 Potential for commercial utilization of current results:

Though the results were obtained in the current investigation using electrohydraulic forming, much of the implication and understanding of principles behind the formability improvement can be quite easily extended to other high rate processes as well. Continuing work on hyperplasticity [90-92] has shown that uniform elongation of rings can be substantially increased using electromagnetic forming.

Although high rate sheet metal forming has seen very little development in recent years, it appears to hold much promise [93]; it can improve formability of difficult-to-form materials, and appears to dramatically reduce springback. Both these efforts are beneficial with regard to the problems currently encountered in forming aluminum auto body panels. The basic technology has been some what developed. Electromagnetic forming is already proven to be amenable for rapid production rates.

In order to speed up commercialization, significant amount of engineering must be done to develop appropriate capacitor banks, coils and related equipment. More work is required to understand what controls the formability of deforming sheets subjected to ballistic boundary conditions. Predictive models for spring back in high velocity forming are also required. As more aluminum is being considered for automobile body applications, it would be advantageous to utilize hyperplastic forming that provides significant formability improvement even on difficult-to-form materials, use of one sided dies, negligible spring back and forming intricate shapes with sufrace detail and sharp corners.
CHAPTER VII

CONCLUSIONS

High velocity processes have been studied for well over four decades, but their commercialization has been marked with abundant caution. Slow acceptance on the part of the industry appears to be due to lack of knowledge on the beneficial effects of the processes over conventional metal working processes.

In this investigation, high plastic strain rates have been shown to improve dramatically the formability of three common sheet forming metals. Specifically, the plane strain forming limit of 6061 T4 Aluminum was found to increase to nearly four times, IF iron to three times and copper to two times their respective low strain rate plane strain forming limits.

The results were observed in forming experiments with a conical die, which represented one of the severest geometries for sheet forming. It has been shown that non-axisymmetric shapes could also be formed in the similar way.
Limit strains were used in the analysis of results and were compared with the help of forming limit diagrams. Since failures often occur in plane strain, formability under plane strain conditions were compared between low and high rate forming. Hence, the results obtained in this investigation are expected to be conservative estimates of benefits in high rate forming.

There have been reports of increased formability in dynamic tensile tests [35-41], but the effects were not so pronounced as is observed in the current investigation. There have been suggestions in the literature of increased biaxial sheet formability, but the available few detailed investigations [21,27] did not report such dramatic increases (comparable to what one observes in superplastic forming) as seen in the current investigation.

Estimated metal velocity in the current investigation could be done in several different ways such as energy balance approach, inertial shearing as well as using Hudson's equation. The estimates varied from 130 to 350 m/s. Strain rates involved in the process were of the order of $10^3$ s$^{-1}$.

The effect of inertia in stabilizing the neck growth has been shown to be partly responsible for the improvement in formability. Analytical models showed that formability could increase at high strain rates and metal velocities. The energies and time scales involved in the process are certainly appropriate for momentum effects to be large. The strongest evidence for this mechanics-based explanation is the observation that this takes place similarly in three materials with otherwise different characteristics. This was also evident from
successful forming of a small sheet lightly taped to the workpiece during the high rate forming.

The compressive stress generated by the impact of the sheet metal on the female die was also found to contribute to increased formability. Analytical estimates showed that such compressive stresses could be as high as 25% to 50% of average flow stress. A thin copper sheet could be successfully formed to fill the conical die if backed by a thicker sheet metal behind it, while the forming was not successful when the order was reversed. This suggested the mechanism of inertial ironing behind formability improvement.

Material constitutive behavior did not appear to have changed as was evident from the terminal hardness measurements. Hardness of the formed components increased within 20%. Also, formability increase did not appear to have resulted from any changes in material constitutive behavior.

From the modeling and experimental results, it could be reasonably concluded that the strain rates and metal velocities in the current investigation were high enough for inertial effects to dominate, but well below the strain rate at which adiabatic localization would have intervened limiting formability. Also, the velocity appeared to be much lower than the von Kármán critical velocity, thus preventing another factor that could have limited the formability.

A relatively simple monitoring of the electrical characteristics of the discharge offers valuable insight into the process. This can be used to monitor the
condition of the spark tips and gap. Bridge wire and salt additives also can be used to improve the process efficiency and reproducibility. Counter pressure exerted by the entrapped air between the sheet sample and female die was found to interfere with the forming process. This was overcome by using a simple vacuum.

Replication of surface details have often been observed in high rate processes. In the current investigation, grid marks from samples were found to be imprinted on the die which were found imprinted on samples formed later. A coin taped to the die was found to be very well replicated with intricate details on the samples. These are not surprising, considering the pressures generated by the shock waves which are comparable to those observed in a typical coining processes.

Without regard to the detailed mechanisms that enhance formability at high velocity, it seems that this may be used very beneficially in commercial metal forming. For example, electromagnetic forming equipment is capable of developing workpiece velocities in excess of 175 m/s [33]. This is well above the critical velocity of most materials.

In order to encourage further study in this area and distinguish this effect from traditional superplasticity which is based on the high rate sensitivity of specially-processed materials, the current phenomenon is termed hyperplasticity.
REFERENCES


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Sheet forming in a conical die lends itself to some simple analytical expressions which could be used to estimate average strain in the deformed component. The shape of the sheet in the initial stages of forming will be free bulging with no die interaction as shown in Figure A.1. This profile is spherical in curvature (as shown on the left and its surface area for a height $h$ and radius of curvature $\rho$ can be generated by revolving the area under the curve $y = f(x)$ shown on the right, around the x axis.

Figure A.1: Spherical surface of sample formed in free bulging and a method to calculate the surface area.
Surface area:

\[
S = 2\pi \int_{x=0}^{x=a} y \, ds 
\]

where the arc length:

\[
ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \, dx
\]

Since the equation of circle is given by

\[
(x - \rho)^2 + y^2 = \rho^2
\]

\[
\sqrt{1 + \left(\frac{dy}{dx}\right)^2} = \frac{\rho}{\sqrt{\rho^2 - (x - \rho)^2}} = \frac{\rho}{y}
\]

\[
S = 2\pi \int_0^h \rho \, dx = 2\pi \rho h
\]

---

Figure A.2: Relationship between sample and die dimensions.
From Figure A.2, \[(\rho-h)^2 + r^2 = \rho^2\].............................(6)

=> \[\rho = \frac{h}{2} + \frac{r^2}{2h}\]..............................................(7)

Therefore, \[S = \pi (r^2 + h^2)\]..............................................(8)

As the forming is continued, at some critical value of "h", the die wall will become tangential to the spherical portion as shown in Figure A.3. Beyond this stage in the forming, the sheet will make contact with the die and an intermediate position is as shown in Figure A.4.

**Case 2:** When \(h = h_{\text{critical}}\):

![Diagram](image)

**Figure A.3:** Profile of sheet in a conical die when it becomes tangential to the die surface.
At this stage of forming, the curved surface of the sheet metal becomes tangential to the conical surface as shown in Figure A.3. The assumption used in free bulging of a circular membrane are still used. In addition, it is also assumed that sticking (infinite) friction exists in the contacted region.

For a die angle of 45°,

\[ \text{In } \triangle CDB, \ CB = r \cos 45° = \sqrt{2} \ r \] \hspace{1cm} (9)

\[ \text{In } \triangle COB, \ CB = OB \cot 45° = \rho \] \hspace{1cm} (10)

Therefore, \[ \rho = \sqrt{2} \ r \] \hspace{1cm} (11)

\[ OC = OD + DC \]

\[ CB \cos 45° = \rho - h + DB \cot 45° \] \hspace{1cm} (15)

\[ 2r = \rho - h + r \] \hspace{1cm} (16)

\[ \Rightarrow \ h = \rho - r = (\sqrt{2} - 1) \ r \] \hspace{1cm} (17)

This shows that at \( h = h_{\text{critical}} = (\sqrt{2} - 1) \ r \) the sheet metal begins to make contact with the die.

\[ S = 2 \cdot \sqrt{2} \cdot (\sqrt{2} - 1) \pi r^2 \] \hspace{1cm} (18)

**Case 3:** When \( h > h_{\text{critical}} \):

During the next stage of forming, the sheet will make contact with the die and take up an intermediate position as shown in Figure A.4.
Figure A.4: Typical configuration of sheet sample in a conical die under infinite sticking frictional conditions.

Spherical surface area = \( 2\pi \rho \cdot (FH) \) ...........................................(19)

Conical surface area = \( \pi \cdot (AD + EF) \cdot s = \pi \cdot (r + \rho \cdot \cos 45^\circ) \) ...................(20)

\[ \text{FH} = \text{OH} - \text{OF} = \rho - \rho \cdot \sin 45^\circ = \rho \left(1 - \frac{1}{\sqrt{2}}\right) \] ...........................................(21)

Therefore, Spherical surface area =

\[ S = 2\pi \rho^2 \left(1 - \frac{1}{\sqrt{2}}\right) = \left(2 - \sqrt{2}\right) \pi \rho^2 \] ...........(22)
Total surface area = \( \pi rs + \frac{\pi ps}{\sqrt{2}} + 2\pi \rho^2 - \sqrt{2}\pi \rho^2 \) ..................................(23)

In the above expressions, \( \rho \) and s need to be expressed in terms of the measured parameters h and r.

DK + KB = r
Since DK = FG = \( \rho \cos 45^\circ \),
\( \rho \cos 45^\circ + s \cos 45^\circ = r \)
\( \Rightarrow \rho + s = \sqrt{2} \) r..................................(24)

Also, DF + FH = h
DF = KG = s \sin 45^\circ
FH = OH - OF = \( \rho - \rho \sin 45^\circ = \rho \left( 1 - \frac{1}{\sqrt{2}} \right) \)
\( \Rightarrow s \sin 45^\circ + \rho - \rho \sin 45^\circ = h \)
\( \Rightarrow s + (\sqrt{2} - 1) \rho = \sqrt{2} \) h...............(25)

Solving equations 24 and 25 yields,
\( \rho = (\sqrt{2} + 1) (r - h) \) .........................(26)
and
\( s = (\sqrt{2} + 1) h - r \)............................(27)

Substituting these in equation 23,
\[ A = \frac{\pi}{\sqrt{2}} \left[ \sqrt{2}rs + \rho s + 2\sqrt{2}\rho^2 - 2\rho^2 \right] \] ..................................(28)

Since \( \rho + s = \sqrt{2} r \) from equation 24,

\[ A = \frac{\pi}{\sqrt{2}} \left[ (\rho+s)s + \rho s + 2\sqrt{2}\rho^2 - 2\rho^2 \right] \] ..................................(29)

\[ A = \frac{\pi}{\sqrt{2}} \left[ s^2 + 2\rho s + 2\sqrt{2}\rho^2 - 2\rho^2 \right] \] ..................................(30)

\[ A = \frac{\pi}{\sqrt{2}} \left[ (\rho+s)^2 + 2\sqrt{2}\rho^2 - 3\rho^2 \right] \] ..................................(31)

\[ A = \frac{\pi}{\sqrt{2}} \left[ (\rho+s)^2 - (\sqrt{2}-1)^2 \rho^2 \right] \] ..................................(32)

From equation 24, \( \rho + s = \sqrt{2} r \) and from equation 26, \( (\sqrt{2}-1)\rho = r - h \)

Substituting these in to equation 32 yields,

The total surface area is =

\[ S = \frac{\pi}{\sqrt{2}} \left[ 2r^2 - (r-h)^2 \right] = \frac{\pi}{\sqrt{2}} \left[ r^2 - h^2 + 2rh \right] \] ...........(33)

The surface area in each of the above stages is summarized in Table A.1. One measure of average strain can be obtained by comparing the change in surface area of the sheet before and after bulging and equating it to the reciprocal ratio of thickness, using constancy of volume. From this measure, average strain
on the sample can be estimated. Such an average measure of true effective strain is also shown in Table A.1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Surface Area</th>
<th>True Effective strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h &lt; (\sqrt{2} - 1) \ r$</td>
<td>$\pi \left( r^2 + h^2 \right)$</td>
<td>$\ln \left[ \frac{r^2 + h^2}{r^2} \right]$</td>
</tr>
<tr>
<td>$h = (\sqrt{2} - 1) \ r$</td>
<td>$2\sqrt{2} \ (\sqrt{2} - 1) \pi \ r^2$</td>
<td>0.158</td>
</tr>
<tr>
<td>$h &gt; (\sqrt{2} - 1) \ r$</td>
<td>$\frac{\pi}{\sqrt{2}} \left[ r^2 - h^2 + 2rh \right]$</td>
<td>$\ln \left[ \frac{1}{\sqrt{2}} \left{ 1 - \left( \frac{h}{r} \right)^2 + \frac{2h}{r} \right} \right]$</td>
</tr>
</tbody>
</table>

Table A.1: Total surface area of sample formed when the sheet sample progressively fills the conical die of semi-apex angle of 45°.