JOINING ENABLED BY HIGH VELOCITY DEFORMATION

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ABSTRACT

Three high velocity joining methods are presented. They are projectile spot impact welding, electromagnetic crimping, and electromagnetic impact welding. Projectile spot impact welding utilizes high-speed bullet to impact metal sheets to a recessed die to achieve a solid state bonding. The bullet velocity ranges from 160m/s to 280m/s. In electromagnetic crimping, aluminum tubes/rings are accelerated by electromagnetic pressure to impact the mandrel to form mechanical interference fit. Residual stress in the tubes/rings provides the crimping strength. In electromagnetic welding, flyer tubes are placed at a specified distance to the base tubes. When the flyer tube is accelerated by electromagnetic pressure to impact with the base tube at an adequate impact angle, high impact pressure will sweep off the surface oxide film to form atomic bonding between flyer and base tubes. Wavy interfaces are normally observed in successful welds.

Finite element modeling is performed to aid the design and understanding of these processes. Three commercial software packages have been used throughout the research. AUTODYN is a nonlinear dynamics code. ABAQUS can handle both static and dynamic problems. MPone is a fully coupled electromagnetic-mechanical code. It has been found that both AUTODYN and ABAQUS are good at solving wave propagation problems,
while MPone is able to provide a reasonable estimation of electromagnetic coupling and mechanical deformation. However, when modeling the electromagnetic crimping problem with each of the three codes, none of them produces fully satisfactory predictions of the process.

The goal of this research is to investigate the joining capabilities of high velocity technologies using both numerical and experimental techniques. The experimental results demonstrate the great potential for using high velocity joining methods in production to save cost and extend current application limits. Although the numerical modeling provides some insight that is useful for developing commercial joining methods, further development is needed to fully capture the complex nature behind these high velocity joining techniques.
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CHAPTER 1

1. INTRODUCTION

High velocity techniques have been widely known for the ability of enabling the fabrication of complex components and forming of high strength or low ductility metals. High velocity forming methods were discovered in the late 1800’s and this area has been intensively studied in the 1950’s and 60’s. Between the early 1970’s and 1990’s, there has been very little research on high velocity forming. However, in recent years, as the automotive industry desires to use more aluminum in automotive body parts for weight and fuel saving, there is resurgence in interest in high velocity forming methods. Additionally, as the aerospace seeks for low cost manufacturing, joining and fabrication of hard-to-joined components benefiting from high energy rate gains significant attention among researchers and engineers.

High velocity forming/joining methods include techniques such as explosive forming, electrohydraulic forming and electromagnetic forming. The distinct feature of these techniques is using force or shock wave generated by explosive, electrical discharge or electromagnetic fields to accelerate the workpiece to high velocity, and the kinetic energy
of the workpiece is the driving force for further deformation. Forming/crimping velocities can range from 100 to 300m/s, and welding velocities can range from 300 to more than 1000m/s. Beside those common high velocity techniques, there is also a small branch of high velocity techniques, which utilizes the high speed projectile to do metal shaping and joining. This branch of techniques is named projectile impact in this research work. Current applications of projectile impact forming are concentrated in the area of penetrating and perforation. However, because it has combined features of high velocity and versatile geometry, applications of projectile impact can be extended to local feature forming and spot welding.

In this chapter, key high velocity forming features will be introduced and discussed. This will include explosive forming, electrohydraulic forming, electromagnetic forming, and projectile impact. Then, finite element modeling attempt of high velocity forming/joining in general will be addressed. Finally, the structure of the thesis will be presented.

1.1.Hi\-\(\text{g} \)h velocity forming and joining methods

High velocity forming methods regain interest in industries because they have unique advantages over conventional metal forming technologies. The following summarizes the common advantages of high velocity forming methods.

(a) \textit{Firstly high velocity forming increasing metal's formability}. For example, aluminum 6061 alloys have low formability, which increases the operation cost compared with
producing the same part using steel. However, when forming aluminum alloys using high rate forming methods, the formability of aluminum can be significantly increased (as shown in Figure 1.1) [1], which may make forming aluminum alloys competitive with traditional steel forming. Other than aluminum, a lot of other metals, such as steel, magnesium alloys and titanium have also been demonstrated to have higher strength under high rate loading [2].

(b) *Despite increasing the formability of metals, the second advantage of high velocity forming is reduced wrinkling.* Inertial forces are believed to be the main reason for this. The experimental work in tube and sheet flanging by Padmanabhan [3] is a great example showing the reduced wrinkling effect.

(c) *The third advantage of high velocity metal forming is high-pressure effect under impact.* When two semi-infinite elastic bodies 1 and 2 collide at an impacting velocity \(V_i\), the impact pressure can be described using the formula in Johnson’s book [4]:

\[
P = \frac{\rho_1 \rho_2 c_1 c_2}{\rho_1 c_1 + \rho_2 c_2} V_i
\]

(1.1)

Here \(\rho_1, \rho_2\) represent the densities of the two bodies and \(c_1, c_2\) represent the longitudinal wave speed in the two bodies. From this equation, it is very easily to attain high pressure under high velocity impact. For example, aluminum-aluminum impacting at 50m/s can generate impact pressure of 680 Mpa. The high impact pressure is very beneficial for imposing surface details in metal forming.

(d) *High velocity forming reduces springback.* Recent work of Padmanabhan [3] and some old literatures in explosive forming [5,6] strongly support that springback can be greatly reduced under high velocity metal forming. The primary reason for this is
that impact causes the residual stains in the sheet metal to be minimized. Reduced springback will increase the dimensional accuracy for die forming of sheet metals, and therefore reduces the cost for die manufacturing. In addition, because of reduced springback, high velocity forming methods can be used as tube assembly technology. This will be addressed in detail in chapter 3.

(e) *Lastly, high velocity forming will reduce manufacturing cost.* This can be accounted in several aspects, including reducing tooling cost in forming, quick lead time production, easy automation, little cleaning before and after operation in welding, reduced inspection and rework for impact welding.

Despite these common advantages, each high velocity technique will also has its own unique features. The following will describe the four different high velocity forming/joining methods separately.

### 1.1.1. Explosive forming

Explosive forming has been recognized as a metal forming and joining method for more than 100 years. The first patent found in the application of explosive forming was issued in England in 1898 (No. 21,840). This patent described a method for joining metal tubes for bicycle frame manufacture using explosive expansion operation. Shortly after that, United States patent was issued to Issac Newton in 1909 (No. 939,702) for using explosive charges to form sheet metal. However, until a long time after that, in 1950’s, researches in the area of explosive forming/joining started to expand. Significant progress
in explosive forming, along with other high velocity forming technologies, including electromagnetic forming, electro-hydraulic forming, has been developed during 1961 to 1973. There are several books [2,7,8] and a recent overview paper by Mynors and Zhang [9] that are good sources for obtaining details in explosive forming techniques and applications, and other high velocity forming technologies.

Explosive forming applications can be divided into two categories, metal forming and metal cladding. Metal forming includes plates (or disks) free and die forming and tubes free and die forming. Figure 1.2 and 1.3 show the schematic views of explosive forming setups and some application examples. The arrangements in figure 1.2 are so called standoff operation, in which the explosive charge is separated from the workpiece by a substantial distance on the order of the part thickness. Contact operations are commonly used in the explosive cladding of materials (solid state explosive welding). Explosive metal cladding/welding will be described later in chapter 4.

The main elements associated with explosive forming are the explosives, the dies, the energy transfer media, and physical arrangements. For explosive die forming, only single-sided die is required, which significantly reduces the manufacturing cost. Die manufacturing techniques for traditional metal forming can be directly adapted here. The most widely used transfer media is water, while sometimes sand or other substances may be used in special cases, such as when high temperature forming is desired. Therefore, understanding the behavior and characteristics of explosives is the first important factor
in conducting explosive operations. There are generally two categories of explosives, high and low explosives. Low explosives such as gunpowder are mostly used as propellants in guns and burn into heat and hot gas. This type of velocity is usually low and less than the speed of sound. High explosives such as dynamite, PETN (pentaerythritol tetranitrate, C₅H₈N₁₂O₄) can be detonated to velocity up to 8000 m/s in or short pulse. High pressure is generated in the detonation front to drive the metals to deform. There are also two types of high explosives, primary and secondary. Primary explosives are relatively easy to detonate. They are used in the form of detonation caps. Secondary explosives have much higher energy content than primary explosives and are more difficult to detonate. Only sharp and intense shock, usually generated by a detonation cap, can be used to detonate them.

In conclusion, explosive forming can be used for the production of components of a wide range of sizes and shapes, especially for low volume production of large size and complex shape components. The materials formed in explosive forming have a higher fracture tolerance and dimensional accuracy. The explosive welding technique also has unique advantages over conventional welding techniques because it is a solid state welding process by nature.
1.1.2. **Electrohydraulic forming**

Electrohydraulic forming is a high velocity technique, which utilizes the discharging of an electrical spark in a liquid to produce shock waves and pressures for metal forming. The most commonly used liquid medium is water or oil. The electrical spark can be generated either by capacitor bank discharging through a gap or a fine wire. In principle, electrohydraulic forming is a variation of explosive forming. It combines the shock wave effect in explosive forming and the concept of capacitor discharging to generate pulse energy in electromagnetic forming, which will be discussed in the next section. The difference between electrohydraulic and explosive forming is the energy source, and subsequently, their applications. Because very large capacitor banks are needed to generate the similar effect as moderate amount of high explosives, electrohydraulic forming is cost intensive for large part production. Instead, it is more suited for use in the workshops and mass production of small parts. The velocity generated in electrohydraulic forming can reach to the order of 200 m/s.

Figure 1.4 shows a schematic illustration of an electrohydraulic forming system. The electrodes are immersed in the water together with the workpiece. The capacitors can be charged to a selected voltage and energy level. When the capacitors discharge (through closing the discharge switch), the high volume energy stored in the capacitors will discharge across the gap/wire at the ends of the electrodes. During the discharge process, the electrical energy is converted into a shock wave in the water to form the workpiece.
The physical arrangement of electrohydraulic forming workpiece and die is similar to that of explosive forming. The different characters are the charging energy and discharge gap or wire size. The energy stored in the capacitor bank is related to the capacitance and charging voltage through the following formula:

$$E = \frac{1}{2} CV^2$$  \hspace{1cm} (1.2)

Here, $E$ is stored energy, $C$ is capacitance and $V$ is charging voltage. Therefore, in order to increase forming energy, one can achieve it through increasing capacitance or charging voltage. In practical usage, the upper limit of the voltage is about 40KV because higher voltage spark gap system is likely to suffer erosion, especially in high energy levels of 20KJ or more. Therefore, increasing in energy that would require voltage level above 40KV can only be achieved by increasing capacitance. The capacitance will be limited by the physical size and production costs of capacitors. The efficiency of a typical electrohydraulic system for transferring stored energy to metal deformation is between 10 to 20 percent. High peak pressure and maximum process efficiency is usually achieved by keeping the system inductance as low as possible. Another factor that directly influence the energy conversion efficiency is the electrodes gap or wire size. This is a more complex topic and will not be covered here. Detailed information can be found in references [1] and [2].

The main application of electrohydraulic forming is tube and sheet forming of small parts. Figure 1.5 shows some examples of electrohydraulic application, in which (a) is a bulged
part and (b) is an assembly part produced by interference fit. Generally, electrohydraulic forming is a versatile and cost saving process. The production rate is normally higher than explosive forming. However, because of the short lifetime of the electrodes and the needs for media containment, electrohydraulic forming is not widely practiced as compared with electromagnetic forming.

1.1.3. **Electromagnetic forming**

Electromagnetic forming (EMF) is a high rate forming technique, which uses the electromagnetic repulsive force generated by an electrical discharge to form materials such as sheet metal and tubes. Beginning in the 1950's, this technology developed rapidly between the late 1960's and the early 1970's, for almost fifteen years. But suddenly, research on this technique was almost abandoned for no apparent reason. Nowadays, as the rapid development of the automobile industry is seeking new technology, interest in electromagnetic forming has been renewed and more researchers have begun to invest more time, effort and money in EMF. To understand this technique, we can discuss EMF from three different aspects, the mechanism of EMF, the process of EMF, the typical forming operations of EMF.

The mechanism of EMF is not as complex as it appears. It is based on the Lorentz Force, which is an electromagnetic force caused by the interaction between the magnetic fields of two current carrying conductors. To illustrate, let us consider two parallel line
conductors near each other. When an oscillating current \( I_1 \) flows through one of them, there is an oscillating magnetic field around the conductor associated with current \( I_1 \). This oscillating magnetic field will induce another current \( I_2 \) in another conductor, and therefore the related magnetic field of \( I_2 \). These two magnetic fields will interact with each other and then generate the Lorentz Force. In the electromagnetic forming process, work-coils and work-pieces can be treated as primary and induced current carrying conductors. Figure 1.6 shows a schematic presentation of a basic electromagnetic assembly. The coil is usually made of copper and aluminum alloys due to its good combination of high conductivity and strength. The workpiece is usually made of well conducting materials. Sometimes, when the work-piece is not made of well conducting material, such as stainless steel, a thin piece of conducting material is added between the work-coil and the work-piece as the conducting driver.

Therefore, all the equipment needed to perform an EMF process is as follows:

A capacitor bank which can store electric energy, a charging circuit for supplying energy to the capacitor bank, a discharging circuit that can supply the primary current, a work-coil, a work-piece, and sometimes with a conducting driver and the die into which the work-piece is to be deformed. The energy storage system is the same as that in electrohydraulic forming, in which the stored energy is determined by the charging voltage and capacitance. The most important variable in electromagnetic forming is the design of a suitable working coil. There are disposable and permanent coils. Disposable coils are made simply by copper wires for experimental work or for feasibility trials.
They will vaporize by large current flow during the discharge of the capacitors. Permanent coils are required for repeated production in industry applications. The design and material selection for permanent coils are far more complex than that of disposable coils. Generally, there are three types of coils based on different forms of production, tubular coils for tube expansion and compression and pancake coils for plate forming. Figure 1.7 shows the typical configuration of those coils.

The electromagnetic forming device can be treated as a simplified RLC circuit. Figure 1.8 shows the typical current traces of the primary and the induced circuit. They both are damped sine waves. The wave frequency is determined by the system inductance and capacitance. Similarly as electrohydraulic forming system, high peak pressure and maximum efficiency is achieved by keeping the system inductance as low as possible.

Electromagnetic forming is mostly used to form and assemble light components, for example, thin tubes and sheet metals. Figure 1.9 shows some typical samples of components produced by electromagnetic process. The application includes expansion, compression of tubes into variable shapes, shaping of disks, and assembly of tubes either by interference fit or by solid-state impact welding. Tube crimping using magnetic pressure and electromagnetic impact welding will be discussed in detail in chapter 3 and 6, respectively.
Electromagnetic forming process has all of the advantages of high velocity forming, but has the added benefit of light tooling, equipment and low cost, fast production. This has made this technology appealing to researches and engineer in recent years. It is the most widely used high velocity technique.

1.1.4. Projectile impact

Projectile impact forming is a general term for a variety of forming techniques. Hammer forming operated either manually or automatically, is probably one of the common formats of projectile impact forming. Hydraulic punch and water hammer forming are two other types. However, the author here will not include all these techniques, instead, projectile impact technology will be referred specifically to a type of technique, in which a projectile such as a bullet or similar shape rod is propelled to a high velocity (over 100m/s) and impacts to the target material to shape, weld or perforate the target materials.

Currently, the most common research in projectile impact is penetration and perforation study in a wide range of situations. For examples, in structure designing applications, researches and engineers are interested in improving the structures’ ability to withstand projectile impacts or other impact loading such as collision. Meanwhile, in production applications, engineers are interested in designing more efficient techniques in hole flanging and cutting processes. A literature search in this area found that within one journal, International Journal of Impact Engineering, there have been more than 200
papers written about projectile penetration and perforation since 1995. A review paper by Corbett, Reid and Johnson published in 1995 [10] covers a significant amount of research work in this area before that time and since 1950’s.

Another research area in projectile impact is shaping and joining. In 1989, research conducted by Salem, Dawood and Al-A’anie demonstrated that spot impact welding could be achieved by high-speed projectile impact. Recent researches by Turgutlu, Al-Hassani, and Akyurt [11,12] emphasized this concept and indicated that the bonded interface has the characteristic of transition from laminar to wavy interface and projectile nose shape played an important role in assessing the bonding zones. The projectile speed in their researches is at the order of 700m/s, similar to that in explosive welding. Meanwhile, research work in OSU by Turner, Zhang and G.S.Daehn [13] shows that by placing an reentrant die underneath two metal sheets and impact them to the die by high-speed projectile, solid state spot welding can be achieved by much lower bullet velocities (160m/s to 270m/s). And the same technique can also be used for local feature forming. The spot impact welding using a reentrant die will be presented in detail in chapter 5.

1.2. Modeling attempt of high velocity forming

As the development of computer capabilities in process simulation, finite element modeling of high velocity forming becomes more and more important not only in the
understanding of the process, but also in the designing of process parameters. Depending on different forming techniques and their development processes, the focus and techniques of modeling could be different in many ways. For example, explosive forming was studied extensively between 1961 and 1973, and because finite element modeling was not very mature at that time, the process was studied mostly by analytical analysis and physical modeling. Although in recent years, new modeling techniques such as arbitrary langrangian-Eulerian (ALE) method and explicit algorithm can enable the combined modeling of explosion and high rate forming, only very few research has been found in the modeling of explosive forming and joining process.

The modeling development of electromagnetic forming is totally different from that of explosive forming. The analytical analysis of EM forming was not studied as extensively as explosive forming in early times, and the arising interest in EM forming has been accelerating the EM modeling activities in recent years. Researchers such as Takasu and Gourdin [14,15,16] have done good researches in EM modeling in late 1980s. After that, for the last ten years, researches in professor G.S Daehn’s group at the Ohio state university by W-F.Pon [17], G.Feton [18], and H.M.Panshikar [19] separately showed promising results in EM modeling.

The early analytical work for describing basic equations of electromagnetic physics was done by Furth et al [20]. Followed work by Bridstall et al [21]and Meaghe r[22] included the analytical analysis of the forming process. At the same time period, Baines et al [23]
modeled EM forming of thin metal parts. In their analysis work, the electromagnetic pressure was calculated using basic physics for electromagnetic interaction between two parallel conductors carrying currents in opposite directions. The forming coil and workpiece were treated as transformer circuit and mutually coupled to each other. The model did not include the workpiece geometry and mutual inductance change during the deformation process. Although their work could not accurately predict the specimen’s behavior under complex deformation motion, they represented the earliest approach used in the field of EM modeling.

From late 1960s and during 1970s, work done by Al-Hassani et al [24] and Jablonski and Wrinker [25] emphasized the development of EM modeling during that time period. In the analysis approach taken by Al-Hassani et al [24], the forming coil and workpiece were combined into a single equivalent circuit. The inductance and resistance calculation included the geometry parameters of the workpiece and coil. The electromagnetic reactions force was calculated from electrodynamics equations. Following that, in the work of Jablonski and Wrinker [25], they took one step further to effectively use equivalent circuit approach by solving a set of first-order differential equations. The equations included the time derivative of the primary and induced currents and velocity and acceleration of the workpiece. This approach was also adapted later in Gourdin et al [15,16] and Takastu et al’s [14] work. The improvements in the work of Gourdin et al [15,16] and Takastu et al [14] are including high strain rate for thin ring expansion and magnetic diffusion effect in modeling sheet metal forming, respectively.
A distinguished feature of recent EM modeling is the development of commercial software packages. Some softwares use loose coupling capability, while others use full coupling capability. In the case of loose coupling, electromagnetic reaction for producing working forces on the workpiece was calculated first in electrodynamics code. Then, the force result was transferred to solid dynamics code to calculate the deformation process. The work in Drysdale et al [26] showed an example of this modeling approach and several codes were also mentioned in the paper. For full coupling of electromagnetic forming modeling, things become very complicated because the complex nature of electromagnetic reaction along with workpiece deformation. The modeling of electromagnetic fields involves the meshing of surrounding space. During the workpiece deformation, the equation solving will involve not only the changes of mutual inductance, but also the changes of mesh domain. Therefore, very few software can do a really great job in modeling EM processes.

In the work of Fenton and Daehn [18], 2D arbitrary lagrangian Eularian (ALE) hydrodynamics code CALE was introduced. As mentioned in the paper, the code was developed at Lawrence Livermore National Laboratory. The ALE methodology allows the flexibility to treat the material in the mesh with either a Lagrangian in a Eularian formulation. In the Lagrangian mode, the mesh deforms as the material deforms. They are tightened together. In Eulerian mode, the material may deform freely in the mesh domain without any effect to the mesh. The CALE modeling in Fenton’s paper includes a
classic Takastu disk problem, a sheet die impact problem and a can forming problem, the results has shown robust simulation and good correlation with experiments. However, CALE is not very widely used because little support is available for CALE user.

Another available commercial software for EM modeling is ANSYS 5.5. It has been claimed that ANSYS 5.5 can do a fully coupling of the EM process. However, the author could not search any published papers for a full coupling EM analysis. The author did find out two papers describing modeling of EM forming using a loose coupling between ANSYS/EMAG and LS-DYNA. In the paper of Oliverira and Worswick [27], the model describes the modeling of EM forming of sheet metal into dome and wedge shape. The results have shown that the simulation is accurate in predicting the displacement of the sheet metal at the center of the coil. However, when looking carefully into the predicted final deformation shapes, the sheet metals have strange deformation behaviors near the edge of the current flow. Especially in the wedge shape forming, there are two “flaps” formed at the edges, which are not normal in experiments.

To the author’s knowledge, the only available 2D and 3D fully coupled electromagnetic-mechanical modeling is Mpone, formerly called MAC and developed by Doug Everhart. The code will be described in detail in chapter 2 and some simulation work will be presented in chapter 5 and 6. References [19] and [28] also have good examples that have shown the capability of this software.
In general, the modeling of high velocity forming is a very complicated process. When simply considering the mechanical deformation process under high velocity, several aspects have to be treated differently: material properties; large deformation; thermal effect, wave effect and contact formulation. None of them are easy and well studied at current stage. Therefore, the EM modeling still has a long and challenge way to obstacle. The work in this research will show some preliminary steps attempted by the author. Some analysis was done by solid mechanics code through obtaining boundary conditions by simple estimation. Some are calculated through full coupling. The purpose is to bring attention and interest for future researches and developments in EM modeling.

1.3. Overview of thesis

The objective of this research is to study different joining techniques under high velocities through numerical modeling and experimental investigation. The understanding and designing of the joining process will be improved through finite element modeling. Meanwhile, the joining feasibility and strength were tested through experiments.

In Chapter 2, the available software capable of modeling dynamic events will be proposed and discussed. The advantages and disadvantages of each code along with examples will be presented.
In Chapter 3, an assembly joining technique enabling the advantages of electromagnetic forming will be introduced. Experimental studies will reveal the stress distribution inside the joint samples. Potential mechanisms and influential parameters for the joining will be discussed. Finite element modeling will also be conducted to better understanding the process and problems related to current modeling capabilities will be addressed.

A review of solid state welding techniques and mechanisms is available in chapter 4. Two solid-state welding processes enabling high velocity impact will be presented in chapter 5 and 6 respectively. The first process described in chapter 5 is projectile spot impact welding using a reentrant die. The experiments will show the joint characteristics and strength, and how the designing parameters will affect the bonding performance. Meanwhile, finite element modeling will play an important role in designing the process parameters. In chapter 6, electromagnetic impact welding will be conducted to demonstrate its feasibility in joining dissimilar materials. Fully coupled electromagnetic and mechanical simulation will be analyzed for the designing of the process. Microstructure examination of the welding interfaces indicates that wavy bonding interface is essential for obtaining optimum bonding strength. Finally, three joining techniques are concluded and compared in chapter 7.
Reference:


7. “High-Velocity Forming of Metals”, a publication in the A.S.T.M.E. Manufacturing Data series (1964)


Figure 1.1 Comparison of forming limit data for 6061-T4 Aluminum obtained from high-rate and low-rate forming experiments [1]
(a) Plate or disk forming setup

(b) Tube forming setup

Figure 1.2  Schematic representations of typical explosive forming setup [2]
Figure 1.3  Examples of explosive formed parts [2]
Figure 1.4  Electrohydraulic forming systems (a) for tubular forming (b) for plate forming [2]
Figure 1.5 Examples of parts produced by electrohydraulic forming/joining [2]
Figure 1.6  Schematic presentation of typical electromagnetic circuit assembly
Figure 1.7  Typical electromagnetic coils (a) expansion coil (b) compression coil (c) plate (pancake) coil [2]
Figure 1.8  Typical current traces for primary and induced currents
Figure 1.9  Typical Electromagnetic formed part [2]
CHAPTER 2

2. DYNAMIC MODELING SOFTWARE

As mentioned previously, high velocity forming involves not only large deformation and different material properties, but also special treatment of the energy initiation systems, for example, explosion and electromagnetic fields interaction. In the case of electromagnetic forming, the main high velocity method used in this research, the fully coupled modeling software would require the ability to solve continuum solid mechanics equations coupled with Maxwell’s equations for electromagnetics. Such a code will include both algorithms for nonlinear, dynamic mechanical solutions and considerations for motional electromagnetic fields distribution in free space. Therefore, developing a fully coupled electromagnetic mechanical code would require an individual or a group of people with great ability in code development and broad knowledge in electromagnetic physics and solid mechanics. However, as loose coupling being another option for electromagnetic forming modeling, unitizing the available solid mechanics codes with some knowledge of electromagnetic physics will make the analysis of electromagnetic forming process acceptable and much simpler.
There are several commercial codes that can deal with nonlinear dynamic problems. Three of them are accessible for the research in our group. They are AUTODYN, ABAQUS/STANDARD and ABAQUS/EXPLICIT, and MPone. AUTODYN and ABAQUS don’t have the ability of modeling electromagnetic fields interaction. MPone has both the ability of modeling dynamic mechanical deformation and electromagnetic fields interaction. These two abilities are also coupled within the code. The following content will first describe these three codes separately, and then a comparison between them will be made through a classic example problem.

2.1. Nonlinear dynamics code: AUTODYN

AUTODYN is developed by Century Dynamics since 1985. It is a commercial general propose hydro code designed for transient nonlinear dynamics in 2D and 3D. The capability of AUTODYN includes solving problems in nonlinear dynamics, fluid and gas dynamics, large strain and large deformation, explosion, shock and blast waves, impact and penetration, and contact problems [1]. It includes multiple analysis techniques such as langrange, euler, Arbitrary Lagrange Euler (ALE), SPH (smooth particle hydrodynamics), and shells. All these techniques can be coupled both in time and space to allow a variety of application problems. The non-linearities in AUTODYN include geometry and material non-linearities, extreme deformations and complex material behavior, contact opening and closing. The integrated analysis environment allows for interactive pre-processing, analysis, and post-processing in the same package. A problem
may be modified during the analysis, deletion and addition of materials and interactions and rezoning (remeshing) of highly distorted elements. AUTODYN provides an extensive material library for user’s selection, for examples, a variety of explosives, liquids, polymers, minerals, metals with different strength models and even air. The strength model of those materials includes more than ten different types of equation of state, nine plasticity models including Johnson-cook, and variety of failure criterions. AUTODYN also provides user subroutine interface for materials and boundary conditions. Online demonstration manuals and different types of tutorials add more flexibility and convenience to users at different levels.

All numerical techniques in AUTODYN require the complex problem to be broken up into a finite number of smaller, simpler problems. This is a discretisation process. The equations need to be discretised both in time and space. The temporal discretisation is the same for different analysis techniques (processor) in AUTODYN. The complete time span is split into thousands of small time steps. Explicit time integration is used for computing required variables for process analysis. But the spatial discretisation is different for different processors. Two different schemes are included, Lagrange and Eulerian. As mentioned before, in Lagrange domain, discretised section moves with material; in Eulerian domain, discretised section is fixed in space. Except SPH, all processors require discretisation of the geometry using a numerical grid or mesh. The discretisation of the geometry includes meshing of the computational space (node and mesh numbering) and meshing of the physical space (assigning coordinates to nodes).
The discretised cells are only meaningful after they are assigned physical location, process type and material property. This discretisation procedure is very unique in AUTODYN. Because of this unique discretisation method, the interaction of different analysis techniques becomes possible in a straightforward way in AUTODYN. However, also because of this discretisation method, the element type is very limited in AUTODYN. Especially dealing with complex geometry, the correct meshing between computational and physical space involves careful calculation and large amount of effort. In addition, the interaction between AUTODYN and other preprocessing and post-processing tools or other analysis codes is very limited, which imparts some difficulties for users.

Dynamic problems always involve with wave propagation. Wavelength shorter than the grid spacing cannot be resolved. Therefore, special treatment is required for shock waves. In AUTODYN, the stability time step is computed based on wave speed and minimum element size and automatically applied to the time span discretisation. In addition, an artificial viscosity is introduced into the solution to smear out shock front over a few cells. The artificial viscosity is based on two terms, a quadratic viscosity for smearing out the shock and a linear viscosity for reducing the oscillations in the smeared solution.

Another feature of AUTODYN is the including of SPH (Smooth Particle Hydrodynamics) technique. In general terms, the SPH method operates by using a set of distributed integration points (particles) to approximate a continuum. The interaction between those particles is controlled by smoothing kernel functions. SPH was invented in
1977 to simulate non-axisymmetric phenomena in astrophysics such as colliding planetary bodies [2, 3]. It is a particle method, which means the computational elements are not grid-cell, but moving points in space where computational information is carried. The absence of background mesh means that SPH can, in principle, treat large deformations while retaining all the advantages of the Lagrange frame of reference. Therefore the problems associated with mesh distortion do not arise in SPH analysis. In addition, the conceptual simplicity of SPH leads to other attractive features such as robustness, ease of adding new physics and ease of doing 3-D calculations. The method has been found useful for the modeling of bomb case fragmentation, impact events and brittle fracture, to name a few [1]. It is still an evolving technique as it is being applied to various new physical phenomena. A good detailed review about the technique can be found in [4].

Figure 2.1 shows an example for impact problem. A long aluminum rod impacts with a rigid wall at different velocities. The aluminum was assumed to have yield strength of 15Ksi. At 30m/s, the rod is bounced back after impact. As impacting velocity goes higher, rod starts to smash onto the wall. This is a very simple problem and was done for the purpose of showing the ability of solving impact problems using AUTODYN.
2.2. General finite element code: ABAQUS Standard and ABAQUS Explicit

ABAQUS is a suit of powerful engineering simulation programs. It consists of two main analysis modules- ABAQUS/Standard and ABAQUS/Explicit. Since it was funded in 1978, ABAQUS has been focusing on FEM methods for 25 years and become a world-wide leader in structural engineering analysis. It has the ability of solving problems ranging from simple linear analyses to the most challenging nonlinear simulations [5]. ABAQUS has an extensive library of elements that can enable the modeling of virtually any geometry. In addition, it has flexible interface for importing geometries from many other design software, such as IDEAS and CAD. ABAQUS also has its own preprocessing and post-processing packages, ABAQUS/CAE and ABAQUS/Viewer. Even though ABAQUS/CAE has a very flexible meshing technique and step-by-step problem setup modules, ABAQUS also can import meshes and boundary conditions from other mesh generation tools such as PANTRAN, Hypermesh. Meanwhile, these tools can interpret the result files from any ABAQUS analysis. All these features make ABAQUS the most widely known and supported finite element analysis software package.

ABAQUS has a wide range of material models that can simulate the behavior of most typical engineering materials including metals, rubber, composite, polymer, foam and even soil and rock. User subroutine can also be integrated with the analysis for defining special purpose material behavior. Since ABAQUS is a general-purpose finite element
codes, it can be used for a variety of applications including stress-displacement analysis, heat transfer, mass diffusion, thermal-electrical analysis, acoustics, soil mechanics and piezoelectric analysis.

Both ABAQUS/Standard and ABAQUS/Explicit can be used for modeling dynamic problems. ABAQUS/Standard uses implicit time integration method, while ABAQUS/Explicit uses explicit time integration method. Explicit time integration is based on previous time step values and the step time is bounded by the smallest element size and wave propagation speed within the material. The advantage of explicit time integration is less computational cost and no convergence issue for complex applications. The disadvantage of explicit time integration is that users must have enough knowledge to input appropriate restrains for obtaining the correct results. Analytical viscosity is also used for dealing with wave propagation in dynamic problems in ABAQUS.

2.3. Coupled electromagnetic-mechanical finite element code: MPone

The initial name of MPone was GEM (Gridless Engine for Multiphysics). It was principally developed by Doug Everhart as the first fully coupled multi-dimensional, multi-physics analysis code. MAC (Multi-physics Analysis Code) was the second name of this code. In year 2003, the code was finally named MPone. MPone uses a unique gridless analysis technique, called the EFG (Element-Free-Galerkin) method, as the main solver. In addition to a deformation and flow code, MPone also includes other physics,
such as electromagnetics, resistive electrical current conduction, and heat conduction [6].

Despite using the gridless analysis technique, continuum finite element and shell element are also integrated with the main solver for flexible solutions.

The main solver in MPone, EFG, is an updated method of SPH. Compared with SPH, EFG uses an enhanced formulation known as Moving-Least-Squares Approximation (MLSPH) to resolve the instabilities in SPH induced by particle tension or uneven distributions [7]. The method is Lagrangian, and the main solution loop uses an explicit time integration routine. The time step for explicit loop should not exceed a certain critical time step that depends on the interparticle distance and speed of sound in the material. Figure 2.2 shows the integration loop of the main solver in MPone. Electromagnetics within the explicit time integration loop is integrated as an implicit loop, which is unconditionally stable. This electromagnetics step calculates eddy currents, magnetic fields, Lorentz forces and Joule heating during each deformation step.

MPone has seven plasticity/damage material models, including Johnson-Cook plasticity/damage model. These models could cover a variety of materials and they can be combined in the analysis to model very complicated material behavior. However, user subroutine is not supported in MPone, which may cause difficulties for modeling experimentally tested new materials. The contact algorithm in MPone includes sophisticated frictional behavior between contacting interfaces. Tied interfaces may also
be defined to simulate bonded behavior. MPone also has a model for representing die surfaces to model non-responding rigid surfaces.

In general, MPone has a unique feature of modeling coupled mechanical-electromagnetic problems. The routine is compact and fast. It is very well suited for analyzing many types of problems. However, it is still in the developing stage. More efforts and supports are needed to make it more user-friendly.

2.4. Comparison of three codes using hopkinson bar impact problem

For the purpose of research in this document, the primary interest is how accurate the code models dynamic problems. To find out that, a classical hopkinson bar problem was chosen to be modeled with each of the codes mentioned above.

Hopkinson bar experiment is a method of testing materials at medium rate of strain. Figure 2.3 shows the setup of a typical hopkinson bar experiment. During the experiments, the pressure gun fires the striker bar to impact with the input bar. The impact will generate compressive stress wave that travels through the input bar to the input bar-specimen interface. At this interface, a portion of the wave will be transmitted through the specimen to the output bar. The remainder will be reflected back into the input bar. Strain gages mounted on the input and output bar will record the strain history at each of the input and output bars. Figure 2.4 shows the typical input and output bar
strain history [8]. From the input and output bar strain history, the strain-stress curve of the specimen can be calculated.

Two-dimensional modeling was used for all the three codes. The input and output bars are 1524mm in length and 19.05mm in diameter. The specimen diameter is half of the bar diameter. The striker bar has an initial velocity of 20m/s. The input and output bars have 600 element in length [9]. Figure 2.5 shows the input bar strain history at the input bar center. Figure 2.6 shows the output bar strain history at the bar center. As seen in figure 2.5, input bar strain histories are very identical from ABAQUS/Explicit and AUTODYN simulation. However, the strain history from MPone modeling shows very low input and reflected strains. All three codes gave very similar transmitted strain wave history as seen in figure 2.6.

In order to obtain the strain stress curve within the specimen, one-dimensional wave transmitting theory was used in this research. Considering the specimen in figure 2.7, force balance and particle velocity continuity are considered in the deviation. Stress in the specimen is (Detail is in reference [8] and [9]):

\[
\sigma_s(t) = \frac{A_pE_p}{2A_s} \left[ \varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_r(t) \right] = \frac{A_pE_p}{A_s} \varepsilon_r(t) \quad (2.1)
\]

The strain in the specimen is:

\[
\varepsilon_s(t) = \int_0^t \varepsilon_s(t)dt = \frac{c_0}{L} \int_0^t \left[ -\varepsilon_r(t) + \varepsilon_i(t) - \varepsilon_r(t) \right] dt = -\frac{2c_0}{L} \int_0^t \varepsilon_r(t)dt \quad (2.2)
\]
Based on these two equations, data in figure 2.5 and 2.6 was collected to calculate the strain–stress curve for different simulation codes. Figure 2.8 shows the results. From the results shown in figure 2.8, both ABAQUS and AUTODYN gave very good results, but MPone had very low stain. The reason for that is not clear to the author at current stage.

Reference:

1. Autodyn users manual, Central Dynamics Corporation, 2003


5. ABAQUS users manual version 6.3, HKS Inc.

6. MPone users manual version 2.0.0, Aces Inc.


8. Bazle A. Gama, Sergey L. Lopatnikov, and John W. Gillespie Jr., Hopkinson Bar Experiments: Analysis and Simulation, UD-CCM research review, April, 24 2002, University of Delaware
Figure 2.1 AUTODYN demonstration: Aluminum rod impacting into a rigid wall at different velocities

(a) 30m/s  
(b) 250m/s  
(c) 350m/s  
(d) 540m/s  
(e) 10100m/s
Start With Initial Conditions

Initial Time Step Constants

Constitutive Models

Physics Equations

Conservation of Momentum

Heat Conduction

Electromagnetics

Conservation of Charge

Advance All Variables

Calculate Time Step $\Delta t$

Figure 2.2  Integration loop in MPone
Figure 2.3  Schematic presentation of hopkinson bar experiment
Figure 2.4 Typical input and output bar history of Hopkinson bar experiments [9]
Figure 2.5  Input bar strain history generated from numerical modeling
Figure 2.6  Output bar strain history generated from numerical modeling
Figure 2.7 Notation used for stress and strain calculation in the specimen
Figure 2.8  Stress-strain curves in the specimen from different modeling code
CHAPTER 3

3. ELECTROMAGNETIC CRIMPING

3.1. Introduction

Crimping is a mechanical joining process that widely used in industrial applications. The joining mechanism is creating inference fit by plastic deformation, without any chemical bonding or fasteners. There are many variants existing and being practiced in the current market, such as wire crimping, double seaming, hemming, and clinching processes. The joining applications range from aerospace, automobile industries to medical devices, sport equipment, and even day-to-day goods. For example, figure 3.1 shows the assembly of aluminum cans. The end of the can is hold by crimping and the tab of the can was hold by spot clinching. Crimping is also very beneficial to auto companies. For examples, figure 3.2 shows that hemming can be used to assembly the inner and outer panel of the car hood. This joining method can replace the equivalent of 80 spot welding [1]. Addition to those examples, crimping can be used to produce leg prosthesis, artery stents in medical applications [2], assemble bicycles and other sport equipment. For such a wide
variety of applications, the traditional approach of producing a crimping joint is to develop a sequence of stages, including calculation, design, and choosing the right technology to do the production. During these stages, the engineers are considering challenge problems such as to ensure dimensional tolerance, and develop reliable processes and technologies for efficient production. Therefore, successful designing and production of crimping joints need combined effort of high-educated engineers and high-skilled technicians, thus increases the production cost.

However, as the development of high velocity forming methods such as electromagnetic forming, simpler and cost effective crimping process utilizing high velocities starts to attract the attentions of engineers and researchers. In the literature, it has been established that high velocity forming can increase dimensional tolerance and minimize springback[3]. This advantage has been utilized by many engineers to design crimping joints by high velocity technologies. For examples, in 1992, a patent was filed to Cherian, et al [4](Patent number 5353617) for sizing metal sleeves using a magnetic field. In their experiments, a conductive coil was placed inside the metal sleeves. The metal sleeves were placed inside a cylindrical die. The die had smooth inner surfaces. During the electromagnetic process, the electromagnetic pressure pulse expanded the metal sleeves to fit into the die inner surfaces. Another very impressive structural crimping example is electromagnetic crimping of high lift torque tubes, which Boeing uses in its 777, 737 and 747 aircraft. Here 0.128” wall thickness aluminum alloy tubes are crimped onto steel yoke fittings. After joining, the tubes were tested for torsion loading. The tubes don’t fail
in the joints, but in the parent materials. Figure 3.3 shows the detail of a typical torque tube joints, and a tube after destructive torsion testing. This electromagnetic crimp replaces a design that was troublesome with respect to fatigue, and the joints have been shown to have a fatigue life equivalent to several times the life of the airframe structures. Except for tubular component assembly, electromagnetic crimping can also be used for hemming and flanging. The advantage of electromagnetic crimping is high dimension tolerance and fast, cost effective production.

Along with the development of crimping technologies and processes, finite element simulation and analytical analysis of those processes have been aided the design and understanding of critical parameters. In static crimping, finite element modeling can be conducted through commercial structural modeling packages. For example, M. Kumosa and his colleagues [5, 6, 7] have performed a series of analysis for the crimping of composite insulators to aluminum end fittings using software packages ANSYS. The stress in the insulator and suitable crimping conditions was analyzed in the papers. The focus has been concentrated on the fracture performance of the insulator. In dynamic crimping processes, the crimping mechanism becomes more complex because of the involvement of high impact pressure and shock waves. Subsequently, the modeling of dynamic crimping is very difficult. Recent work of Sergey Golovashchenko proposed useful hints for designing and analyzing the electromagnetic crimping process. For examples, in his research of tube expansion crimping, wave propagation was considered to be important in the crimping process [8]. Both pressure history and inner-outer tube
gap were shown to have significant effect on crimping joints. In his research for tube compression crimping, he proposed an analytical designing methodology for achieving high tensile strength joints [9]. The mandrel used for tube compression crimping was designed with grooves to assist joining strength. It has been shown that increasing the groove width makes the groove easier to fill with the tube material, but decreases the joint strength. Increasing the groove depth makes the tube material harder to fill in, but increases the axial strength of the joints. However, he didn’t prove any information about shock wave effect and gap influence on the final joint performance.

During the practice in electromagnetic forming group in the Ohio State University, tube compression crimping was found to be very universal. With sufficient energy, tubes can be always crimped tightly to mandrels. The joint strength was found to near the tube material yield strength even with a large gap between tube and mandrel initially [3]. Mandrels without grooves were also effectively crimped. However, no information in the literature has been found to explain and discuss the mechanism of this joining phenomenon. In this chapter, effective electromagnetic tube compression joining experiments were designed and performed to prove the high joint strength of tubular crimping joints; and strain distribution in the tubes was measured and analyzed to understand the controlling parameters for the joints. Finally, finite element modeling was attempted to understand the difference joining mechanism between static and dynamic crimping processes.
3.2. Methodology and experimental setup

Two sets of experiments were designed to investigate the joining strength and mechanism of electromagnetic crimping. The objective of design I was to achieve high tensile crimping strength. Figure 3.4 shows the main tools for crimping design I. The tube is aluminum 6061-T6 with outer diameter of 1.125” and wall thickness of 0.066”. Nuts are 1/2-13 Hex jam nuts purchased from current market. Four nuts were screwed on a rod to provide the base for crimping. The position of the nuts on the rod were remained the same for every crimping process. The coil was designed by Vincent Vohnout. High conductivity copper was chosen for this coil design to provide both enough strength and conductivity. The coil is 1” thick and has 1.148” hole inside to provide concentrated current flow in the internal surface of the coil. The 1.148” hole was tapered down to 0.5” in height, which is the coil’s working area during electromagnetic process. The coil has two sleeves, each connected to the capacitor bank to form a current loop. The two sleeves have mylar insulation between them during the experiments. Figure 3.5 shows the equipment and setup for the experiments. The capacitor bank has full energy of 16KJ and 8 capacitors. The working energy can be chosen from the control panel. The tube was placed inside the coil, which has mylar insulation around the hole and outside of the tube. The rod with the nuts was placed inside the tube. During the experiments, a chart with adjustable height was placed beneath the coil to support the rod and tube. The experiments were conducted in four steps. In step one, the top of the rod was adjusted to the same height as the tube so that the first nut on the top was inside the coil working area.
When electromagnetic pressure was generated during capacitor charge and discharge, the tube was crimped onto the first nut. The position between the nuts and the tube was then fixed during sequential process. In step two, the second nut on the top was adjusted inside the coil working area and tube was crimped onto the second. In step three and four, the tube and rod were reversed and step one and two were then repeated. The only variable in this set of experiments was the bank energy. 70%, 80% and 90% of full energy, which corresponds to 11.2 KJ, 12.8 KJ and 14.4 KJ respectively, were tested for the same tube and rod setup.

The second set of experiments was inspired by both design I and thesis work of Mahadevan Padmanabhan. The capacitor bank and coil used for design II are the same as design I. The tube was machined to 0.5” wide rings. Additionally, instead of crimping the tube to the nuts, the rings were designed to crimp onto 1” solid mandrels. After crimping, those crimped samples were cut and the strain relief during cutting was measured by strain gages. Figure 3.6 shows the crimped samples and rings after cutting.

The main goal of design II was to measure the crimping strain for different mandrel materials. As shown in static crimping simulation, the material’s young’s modulus plays an important role in the joining process. However, when considering dynamic processes, it is not known whether they will influence the results in the same manner. Therefore, G-10, aluminum and steel mandrels were chosen for conducting the experiments to understand the effect of material property on the crimping process. Three variables were
measured during the experiments: ring diameter immediately after crimping, strain change during the cutting and ring diameter after cutting.

3.3. Experimental results

3.3.1. Results for design I

Figure 3.7 shows the joint samples. The nuts were crimped and locked into the tubes. After crimping, the rod was removed, leaving the nuts tight in the tube. When the forming energy was increased, the tubes were deformed more severely and it was difficult to remove the screw rods.

The joint samples were then tested for tensile strength and fatigue performance. The screws were placed into each pair of the nuts on two sides of the samples and loaded axially through MTS machine. The performance of the crimped samples under tensile loading is shown in Figure 3.8. From the ultimate tensile strength value (310Mpa) of aluminum 6061-T6, the theoretical tensile strength of the original tube before crimping was calculated to be 9850lbs. When comparing the tensile strength values in Figure 3.8, it was shown that as the crimping energy increases, the tensile strength of the crimped sample approaches the theoretical strength of the original tube. When the crimping energy is 14.4KJ (90% of the full bank energy), the tensile strength value of the crimping samples is about 80% of the theoretical strength of the original. This can be used for most applications. Figure 3.9 shows the tensile failure characteristics of samples with different
strengths. When the samples were crimped under low energy, their tensile strengths were low and the nuts were easily removed without damaging the tubes. When the samples were crimped under moderate energy with medium strength, the nuts could be removed but left cracks in the tubes. When the samples were crimped under energy of 12.8 KJ or greater, the nuts were very tight in the samples and the test broke in the base tube as shown in Figure 3.9 (c). Even after tensile testing, the nuts were still tight in the tubes. Following the tensile strength test, two samples were selected for fatigue test using an Instron machine (model 1322). 400-4000lb sine wave loading were applied to the samples. The loading has a cycle wavelength of 0.5s. The samples under loading were both crimped under 80% of full energy (12.8KJ) and cycles to failure were 2415 and 2958 cycles. In addition, the failure occurred in the base tube where a high stress concentration may be present during crimping. However, this experiment was not carefully designed, as only standard materials and tools were used for crimping. Future research of improved design may achieve both high strength and high fatigue life crimping samples.

3.3.2. Results for design II

Design II was experimentally tested for more than 30 samples. After testing, the outer diameters of all rings were measured as 28.3mm independent of mandrel materials. Then strain gages with resistance 120 mini ohms and gage factor of 2.12 were mounted on the outer surface of each ring to measure the hoop strain change. The cutting was done on a
band saw. Figure 3.10 shows the hoop strain change recorded by the strain gages during cutting. As clearly shown in figure 3.10, the ring outer surface hoop strain increases as increasing with crimping energy. At the same energy level, however, there is no clear correlation between different mandrel materials. Additionally, the strain changes recorded during cutting are all negative values, which indicates the residual hoop strain in the ring after crimping is tensile. This is consistent with the theory that tensile hoop strain in the rings provides the crimping strength.

The second important variable measured was the ring diameter change after cutting. The diameters were measured 90° from the strain gages. Figure 3.11 shows the result of measured diameter changes. In low energy (4.8KJ), there is little variance in the ring diameter when using different mandrel materials. When energy is 8KJ or more, rings crimped onto G-10 mandrels have smaller diameter change after cutting. The reason for this behavior will be explained in the discussion section.

3.4. Finite element modeling of the crimping process

Although experiments have shown the joining ability and strength of crimping aluminum to different mandrels, there is no theoretical or numerical evidence to provide design confidence for researchers and engineers. Therefore, the next phase of research will focus on numerical modeling of the crimping process, both static and dynamic cases. In both
the static and dynamic modeling, geometry and material properties of design II were considered.

### 3.4.1. Finite element modeling of static crimping process

The static crimping was modeled by applying pressure around the 0.5” wide aluminum rings. ABAQUS/STANDARD was chosen for this simulation because of its versatile ability for structural modeling. Since the setup was perfectly axisymmetric, 2D axisymmetric modeling was attempted as shown in Figure 3.12. Beside its axisymmetric symmetry, the setup is also symmetric to the centerline across the mandrel and ring. Therefore, only half of the mandrel and ring was included in the modeling. As shown in Figure 3.12, the pressure is applied on the outer surface of the ring. To avoid edge effect, the ring was divided by three identical sections. 100Mpa, 300Mpa and 400Mpa pressure was applied to top, middle and bottom sections, respectively. This pressure distribution is close to the electromagnetic pressure generated in the experiments. The mandrel was modeled using three different materials; aluminum, G-10 and steel. Table 3.1 listed the material properties included in the numerical models. Bias mesh technique was applied to the mandrel to reduce the problem size. Both mandrel and rings were meshed using 4-node axisymmetric solid element.
<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m$^3$)</th>
<th>Yong’s modulus (Gpa)</th>
<th>Poisson’s ratio</th>
<th>Yield strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (6061-T6) [3.11]</td>
<td>2700</td>
<td>69</td>
<td>0.33</td>
<td>275</td>
</tr>
<tr>
<td>G-10 [3.10]</td>
<td>1860</td>
<td>28</td>
<td>0.18</td>
<td>345</td>
</tr>
<tr>
<td>Steel (1018) [3.11]</td>
<td>7780</td>
<td>207</td>
<td>0.28</td>
<td>370</td>
</tr>
</tbody>
</table>

Table 3.1 Material properties for modeling of the static crimping process

The static crimping process was modeled with two steps. Step I is compression, in which the ring was compressed under the applied pressure stated above. Step II is springback. In this step, the applied pressure was removed and ring underwent an elastic recovery process. The residual hoop stress inside the ring shows how strong the ring is crimped onto the mandrel. Figure 3.13 shows how the ring hoop stress changes during compression and springback steps. Note that for all three mandrel materials, there is a small step change for the hoop stress. This is caused by the contact between the ring and mandrel. After springback, the hoop stress in the ring for steel and aluminum mandrel both goes to zero, which indicates that aluminum ring can’t be crimped to steel and aluminum mandrel by applying static pressure. However, for G-10 mandrel, because it has much smaller young’s modulus comparing to aluminum ring, the crimping stress is in
the same order as the yield stress of the ring. Figure 3.14 shows the final geometry with hoop stress contour plot for three different mandrels.

3.4.2. Finite element modeling of dynamic crimping process

Dynamic crimping process is different from static crimping process in two aspects. First is the material behavior. In dynamic crimping process, large pressure is generated at the material interface during impact, and strain rate is higher than static crimping process. Therefore, rate dependent material strength model with shock equation of state was used in the modeling. Second is shock wave effect. When the ring impact with the mandrel, compressive stress wave will be generated at the material interface. The stress wave in the mandrel travels through a distance of mandrel radius when encountering the boundary. However, the stress wave in the ring only travels through ring thickness, it will then be reflected back from ring outer surface. The distance through mandrel radius is almost ten times of that through ring thickness. Therefore, the stress wave in the ring will become very complex because of multiple reflections through ring inner and outer surfaces. From the previous modeling of hopkinson bar, ABAQUS/Explicit and AUTODYN both can accurately capture stress wave propagation in metals. Therefore, both codes have been used for dynamic crimping modeling, however, Mpone was also performed to model the induced current in the ring.
In ABAQUS, dynamic crimping modeling was performed using the same setup as static modeling as shown in Figure 3.12. When applying a pressure pulse of 400Mpa with time duration of 18μs, both ring and mandrel were heavily deformed. Therefore, the pressure pulse was decreased to 200Mpa with time duration of 18μs. After both ring and mandrel approached a stable state, the residual hoop stress in the ring was calculated by averaging the hoop stress in each element. However, zero hoop stress was observed in the ring. The result didn’t change with different pressure magnitude and duration. The modeling failed using ABAQUS/Explicit.

Since ABAQUS couldn’t predict the right residual stress, AUTODYN was then tried to model the dynamic crimping process. The same setup in figure 3.12 was used in AUTODYN. Rate dependent plasticity and shock equation of state was considered for material behavior. Pressure pulse 400Mpa with 18μs time duration was applied on the outer surface of the ring. After both ring and mandrel stabled down, the residual hoop stress of each element was then averaged to obtain the residual hoop stress of the ring. This time, the residual hoop stress is a large value (260Mpa) and it is compressive. This value is also contradictory from the experimental results, which will be shown later.

3.5. Discussion of ring crimping mechanism

Since both ABAQUS/Explicit and AUTODYN couldn’t give a reasonable estimation of the ring residual stress after crimping, only experimental results will be discussed to
understand the stress distribution in the ring. As seen in figure 3.10, during the cutting process, the strain response captured by the strain gage in ring hoop direction is compressive, which indicates that the hoop strain of the ring before cutting is tensile.

Now, we need to consider the crimping process carefully. During the initial pressure loading, the ring was in compression in both radial and hoop directions. When the ring started to impact the mandrel, a large impact pressure was generated at the interface to inhibit the compression behavior of the ring. Meanwhile, stress wave generated during the impact was traveling back and forth between the ring inner and outer surfaces. All these factors worked together to cause the tensile state of the ring hoop direction. This residual tensile stress in ring hoop direction provides the crimping strength.

The hoop stress/strain in the ring can be considered as two parts. First is the tensile strain by bending, which can be measured by radius of curvature change during the cutting. The strain induced by bending will be balanced inside the ring because bending strain along ring thickness is linear distribution. The inner surface bending strain is compressive and the outer surface bending strain is tensile, and they are equal in magnitude. This strain doesn’t account for the strength of the crimp. The second is the stretching strain in the ring. It is tensile along the thickness of the ring. This stretching strain is the main factor account for crimping strength. Figure 3.15 is the calculated strain change due to bending effect. Figure 3.16 is the calculated stretching strain in the ring. The stretching strain was calculated by subtracting the bending strain change from the total strain change. As seen in figure 3.16, before cutting, the stretching strain in the ring hoop direction is tensile. It
increases as increasing crimping energy. Compared for different mandrel materials, G-10 is the most efficient material by generating highest stretching strain at the same energy. Therefore, G-10 mandrel is good for both static and dynamic crimping process.
Reference:

1. Thomas M. Finelli and Bruce G. Kelly, “Design and manufacturing consideration for aluminum hood assemblies”, SAE paper # 770336


4. Cherian; Abraham (Webster, NY); Herbert; William (Williamson, NY), “Method of sizing metal sleeves using a magnetic field”, US patent number 5353617.


8. Sergey Golovashchenko, “Mechanics of pulsed pressing for assembling tubes”,
The VII-th National conference on Technologies and Machine-Tools for Cold Metal

9. Sergey Golovashchenko, “Methodology of design of pulsed electromagnetic
joining of tubes”, Proceedings: the second global symposium on innovation in
material processing and manufacturing: sheet materials, Feb. 11-15, 2001 TMS
annual meeting, New Orleans, Louisiana.


Figure 3.1  Aluminum Can Assembly using crimping techniques
Figure 3.2  Car door panel assembly using hemming technique
Figure 3.3  Torque tubes in electromagnetic crimping, (a) Steel yoke (b) Cross section of the torque carrying joint (c) Tube after torque overload testing, failure is outside the joint region
(a) Tube and nuts for crimping

(b) Copper coil used for crimping

Figure 3.4  Main tools for crimping design I
(a) Capacitor bank

(b) Closer view of the coil and setup

Figure 3.5  Equipment and setup for crimping design I
Figure 3.6 Crimped samples and rings after cutting
Figure 3.7  Crimped samples for design I
Figure 3.8  Tensile strength of the samples at different crimping energy
Figure 3.9  Failure characteristics of samples with different strength
Figure 3.10  Hoop stain change of the ring outer surface during cutting

\[ y = -0.2379x + 0.22 \]

\[ y = -0.2802x + 0.4233 \]

\[ y = -0.2006x + 0.0321 \]
Figure 3.11 Diameter change of the ring after cutting
Figure 3.12   Modeling setup for static crimping
Figure 3.13  Modeling results of static crimping for design II under 400Mpa pressure
Figure 3.14  Deformation geometry after springback shown in hoop stress contour plot for three different mandrel materials.
Figure 3.15  Calculated bending strain
Figure 3.16  Calculated stretching strain
CHAPTER 4

4. LITERATURE REVIEW OF SOLID STATE BONDING

4.1. Introduction

Solid-State welding is a joining process where two surfaces can be bonded at temperatures below the melting point of either workpiece, without the addition of brazing or solder filler materials. Pressure may or may not be applied. This bonding technique is usually classified into two broad categories: diffusion bonding without a large amount of plastic deformation; and bonding accompanied by extensive plastic deformation, such as roll bonding. Each of both categories has different specific techniques regarding the difference in energy supply, temperature range and bonding time duration [1].

The main advantage of solid state welding is the ability to join dissimilar materials. Dissimilar material joints are necessary in applications that require a variety of material components within the same part. For example, in high DC bus systems, often aluminum
is chosen for one part of the system and copper is chosen for another. A copper-aluminum transition is needed to connect them [2]. Usually, an appropriate method of producing dissimilar material joints can be determined by examining the phase diagram (assuming it exists or it is possible to achieve it). For instance, if the phase diagram indicates the existence of intermetallic compound with poor mechanical properties, then a solid state welding process may be applied. However, there are also some limitations in solid state welding techniques because of the limitations of energy supply, equipment setup and material properties. This will be discussed in detail later on in this chapter.

The study of solid state welds necessarily leads to studies of the interfacial region because it is the most likely site for failures. The interfacial failure could be related to the properties of one particular material or complex combinations of several materials. Currently, metallurgical tools (such as transmission electron microscope, scanning electron microscope) provide us opportunities to study interfacial behaviors at atomic level and their proper correlation to the macroscopic level. At the same time, simulation techniques have also been developed to provide insights at these levels.

The simulation of a welding process is a complex task involving the interaction of thermal, mechanical and even metallurgical properties of the materials. Therefore, the simulation is highly nonlinear and has transitions from local zones to global structure. Currently, Finite element method can provide us enough capability to model nonlinear thermal-mechanical coupled problems. However, it has limitations in modeling the
metallurgical phenomena [3]. Smooth particle hydrocode (SPH) can be used to model the interface characteristics (wavy, planar etc), but it also has the same limitations in modeling the metallurgical phenomena [4].

This chapter will begin with a review of important solid state welding techniques and their applications, followed by some arguments regarding the bonding mechanism of solid state welding. Then, general ideas of modeling welding processes will be proposed.

4.2. Important solid state welding techniques and their applications

Generally, to achieve good solid state bonding, it is necessary to obtain an extremely close contact through the bonding interfaces, within the range of mutually attractive forces. However, this is very difficult at the bonding interfaces because it is usually difficult to avoid any microscopic roughening and surface contaminants, such as oxide films. Therefore, it is necessary to bring intimate contact of interfaces through proper amount of plastic deformation [5]. Different solid state welding techniques have different forms of energy supply to cause plastic deformation and obtain required welding temperature ranges.
4.2.1. Friction Welding

Friction welding is a solid-state joining process that produces coalescence by the frictional heat produced by two rubbing surfaces [6]. This method relies on the conversion of mechanical energy to thermal energy without other heat sources. The process typically consists of three stages as shown in Fig.4.1: initiating stage to reach proper rotational speed, rubbing (or friction) stage to obtain optimum temperature range and forging stage to complete the weld. The principle variables that are controlled to provide the necessary combination of heat and pressure to form the weld are rotational speed, axial pressure and welding time.

A variety of similar and dissimilar metals, for example aluminum alloys, aluminum and cooper, can be joined by friction welding. Details of the list can be found in Welding Handbook, Volume 2, 8th edition. Since the welding energy of friction welding is from rotational kinetic energy, the basic requirement of the application is one of the members to be joined, must have axial symmetry. Therefore, friction welding is frequently used for tube to tube, bar to tube, and bar and tube to plate joining. The development of linear friction welding, occurred approximately twenty years after rotational friction welding, and offers opportunities to weld non-axial symmetry components. However, it is not as widely used as rotational friction welding [5,6].
4.2.2. Explosive Welding

Explosive Welding is a solid state joining process that uses explosive energy to accelerate one of the workpieces to a speed at which a metallic bond will form, when it strikes the other workpiece. The weld is produced in a fraction of a second through plastic flow of the metals on the workpiece surfaces. Fig.4.2 shows a typical component arrangement for explosive welding. During the welding process, the prime component is moved toward the fixed base component upon detonation of the explosives. Usually, a standoff distance is applied initially between the prime and base components to allow acceleration of the prime component. When the prime component collides with the base component, complex mechanical and metallurgical actions occur to form the weld [5,6]. The important interrelated process parameters for explosive welding are collision velocity, collision angle and prime component velocity. Because of the complicated nature of the explosive welding process, these parameters are often specified for particular metal configurations through a series of trial-and-error experiments or are based on the intuition of an individual with previous experience.

Explosive welding has a wide range of joining abilities for material combinations ranging from those that are commonly joined by other welding processes, such as carbon steel to stainless steel, to those that are metallurgically incompatible for fusion welding, such as aluminum or titanium to steel. The size of explosive welds can range in application from those involving less than 0.1g of explosive and 0.0004 in² bond area to those using 2000
lb of explosive for 300 ft\(^2\) bond area. The geometric configurations that can be explosive welded are those which allow a uniform progression of the detonation front, including flat plates as well as cylindrical and conical structures [1,6].

### 4.2.3. Ultrasonic Welding

Ultrasonic welding is a solid state welding process in which coalescence is produced at the faying surfaces, by the application of high frequency vibratory energy, while the workpieces are held together under moderately low static pressure. Fig.4.3 shows the typical components of an ultrasonic welding system. The vibration energy is generated in the transducer, and transmitted through a coupling system to the sonotrode tip, which is in contact with one of the workpieces. Clamping force is applied during the welding process to accomplish sound welds. The basic and important variables of ultrasonic welding are ultrasonic power, vibration frequency, clamping force, and welding time [1,6].

Most metals and their alloys can be ultrasonically welded, for example, copper and aluminum alloys, steels, precious and refractory metals, and titanium. Multi-layer similar or dissimilar metal welding can also be achieved with ultrasonic welding. The basic limitations of ultrasonic welding are the workpiece sizes and geometries. This is because there is an upper limit to ultrasonic power supply and the geometries of the workpieces
have to supply adequate joint overlap, access for the sonotrode tip to contact them, and conditions for applying the clamping force.

4.2.4. Roll Bonding

Roll Welding is a process in which two or more sheets or plates are stacked together and passed through a rolling mill to achieve solid state bonding through sufficient plastic deformation. The process can be classified into cold roll welding and hot rolling, depending on different operation temperatures. Typically, cold roll welding is performed at room temperature and hot rolling is performed above recrystallization temperature.

In roll welding, surface preparation is very important because any surface inclusions will significantly reduce the welding strength. To accomplish a sound weld, threshold deformation (typically greater than 60% in cold roll welding) must be exceeded to keep the parts together. Hot rolling will require lower threshold deformation, but it has higher risk of metal oxidation. Increasing pressure will promote welding by minimizing the nonuniform distribution of normal stress near the outer edges of the parts being rolled. The most common metals that are roll welded are low-carbon steels, aluminum and aluminum alloys, copper and copper alloys. Low-alloy steels, high-alloy steels, nickel-base alloys, and titanium and titanium alloys have also been roll welded. Roll welding is widely used in the manufacturing of metal laminates, fabrication of heat exchangers and cladding of metals [1].
4.2.5. **Diffusion Bonding**

Diffusion Bonding is a solid state welding process that produces coalescence of the workpiece surfaces by the application of pressure at elevated temperature without macroscopic deformation or relative motion of the workpieces [6]. A solid filler metal (diffusion aid) may or may not be used between the workpiece surfaces. Joining occurs at a temperature around 0.6 to 0.8 of the melting temperature of the joining material (for dissimilar materials joining, it refers to the low melting temperature material).

During diffusion bonding, temperature is the most influential variable because it determines the microdeformation of the contacting asperities as well as the diffusion rate of contacting interfaces. Pressure is important to enhance the contacting area of joining interfaces. The time required to form the joint depends on the temperature and pressure applied and the material properties. A wide variety of similar and dissimilar material combinations, including alloys of titanium, nickel and aluminum, can be successfully diffusion welded. Generally, metals that have a high solubility for interstitial contaminants are easily diffusion bonded. For example, the joining of silver at 200°C, requires no deformation to break up and disperse oxides, because silver oxide dissociates completely at 190°C [1]. Other metals that have low solubility for interstitials, such as aluminum and nickel alloys, are not readily diffusion bondable. Surface preparation must be controlled carefully for those metals to enable a sound diffusion bond.
4.2.6. Summary

All the technologies described above fall into the same category of solid state welding. They have the same advantage of joining dissimilar materials quickly and efficiently. However, each technique has its own advantages and disadvantages, therefore they are supplemental to each other rather than substitutive. The following characteristics make them distinguishable from each other.

First, different equipment is used to supply the bonding energy. This may give different limitations to the parts geometries and sizes. For example, ultrasonic weld thickness is limited by the available ultrasonic energy. Friction weld geometry is limited to axial symmetric parts. Explosive weld geometry needs the proper position for putting explosives. Second, there are different requirements for surface cleaning. Explosive, friction and ultrasonic welding have no restriction on surface cleanliness. This is because the workpiece interfaces are under large plastic deformation or rubbing in the welding processes, and the interface contaminant could have been extruded or dispersed from the joining area. However, in roll bonding and diffusion bonding, surface cleanliness is very important because surface contaminants are the primary bonding barrier for achieving a good bond. Third, they have different welding temperature ranges. Usually, ultrasonic and cold roll bonding have lower temperature ranges than those of explosive, friction and diffusion welding. Higher temperature may have higher risk of producing intermetallic
compounds, thus the process variables must be carefully controlled and coordinated to minimize their influence on the welding strength. Finally, they have different welding times, which determine their economic effects and commercial applications. For example, diffusion welding, which takes up to tens of minutes to form the bond, has limited development compared to other bonding techniques. Table 4.1 gives a more comprehensive comparison between these techniques.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Energy supply</th>
<th>Welding temperature</th>
<th>Welding time</th>
<th>Surface preparation</th>
<th>Surface extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction welding</td>
<td>Rotational kinetic energy</td>
<td>High (more than 50% of melting temperature)</td>
<td>Several seconds</td>
<td>Not necessary</td>
<td>Not studied</td>
</tr>
<tr>
<td>Explosive welding</td>
<td>Explosion energy</td>
<td>High (near or exceed melting temperature)</td>
<td>Less than a second</td>
<td>Not necessary</td>
<td>High (up to 150%)</td>
</tr>
<tr>
<td>Ultrasonic welding</td>
<td>Ultrasonic vibration energy</td>
<td>35%–50% of melting Temperature</td>
<td>0.1–5 seconds</td>
<td>Not necessary</td>
<td>Low</td>
</tr>
<tr>
<td>Roll bonding</td>
<td>Plastic deformation</td>
<td>High (hot rolling); low (cold rolling)</td>
<td>Usually several passes</td>
<td>important</td>
<td>High (at least 60%)</td>
</tr>
<tr>
<td>Diffusion welding</td>
<td>Thermal and surface energy</td>
<td>60%–80% of melting temperature</td>
<td>Several to tens of minutes</td>
<td>important</td>
<td>Very low</td>
</tr>
</tbody>
</table>

Table 4.1 Comparison between different solid state welding techniques
4.3. Bonding mechanism of solid state welding

Due to the complexity involved in the solid state welding process, there is no generally accepted or fully developed theory for the bonding formation of the solid state bonding techniques described in section 4.2. Possible mechanisms proposed in the literature include: (1) melting, (2) diffusion, (3) recrystallization, (4) adhesion, and (5) interfacial reaction. In this section, each of these mechanisms will be discussed in light of the relevant evidence. In addition, interfacial morphology has also been studied extensively to better understand the bonding conditions and mechanism of the explosive welding process. Therefore, a general description of the interfacial characteristic during explosive welding will be presented to support some of the bonding mechanisms.

4.3.1. Melting

Localized melting at the interface has been occasionally observed in explosive, friction and ultrasonic welding processes [7,8,14]. Localized melting is considered to be a direct consequence of temperature rise in the workpieces, which is caused by frictional heating during the welding processes.

In the ultrasonic welding of aluminum and copper alloys, Kreye [7] reported that a thin surface layer of very fine grains (0.05-0.02μm) was observed at the weld interface using TEM examination. Based on cross-sectional metallography, Ainbinder and Tikhomirova
observed that oxide inclusions were vigorously mixed in the bonding zone of copper after a weld time of two seconds [9]. They both claimed that their observations were due to a process of short time melting and rapid solidification during welding. Aside from their observations, features attributed to melting have not been commonly observed in ultrasonic welds. Joshi [10] reported that there was no evidence of cast structure, heat affected zones, or intermetallic compounds occurring at the interface of various joint made in Al, Cu, and Au. Furthermore, at the liquid nitrogen temperature (-195°C) and without significant increase in welding power, Joshi [10] and Harman [11] have successfully made Au-Au and Al-Al welds, respectively. Based on these results, all these authors suggested that melting is not necessary for the formation of ultrasonic welds.

In the explosive welding of copper to copper, Holtzman and Cowan [12,13] indicated that at the bond interface, a column structure typical of a cast structure was formed. They also found that in the explosive bond of copper to nickel, a hole in the center of a large pocket of material was developed during the welding process. They ascribed the hole to a shrinkage cavity resulting from solidification of material. In addition, in the explosive welding of similar aluminum alloys, Kreye [7] reported that the bonding area consists of a 0.4 to 0.5µm wide zone with small grains of only 0.1 to 0.3µm size, and he concluded that a continuous melting layer or melt pocket of wavy interfaces largely contribute to the forming of explosive bond. Continuous molten layers or melt pockets at various explosive joint interfaces have also been observed by many other researchers [15,16]. However, successful bonds have also been made without melting [13,16]. Therefore,
even with the observation of melting in most metal combinations, many researchers claimed that melting is only a byproduct in the welding process, excessive melting may produce intermetallic compounds, which may lower the bonding strength [15,16,17].

In the friction welding of nickel to steel, the measured temperature at the interface has been found [18] to exceed the melting point during the welding process. Other researchers have also indicated local melting in friction welded aluminum bar and copper to steel bars [19,20]. However, there is no evidence stating that melting is an influential bonding mechanism in friction welding.

Temperature measurements made in the bonding area provide further information on melting as a welding mechanism. The maximum temperatures measured in ultrasonic welding generally, were not higher than 50\% of the absolute melting temperature of the materials, except for Al pairs. In friction welding, typical welding temperature measured was also under the melting temperature of joining materials. Table 4.2 lists a sample of the available data for these temperature measurements. However, it should be noted that this data can only be taken as indirect evidence, because it is very difficult to obtain a reliable measurement of interfacial temperature. Furthermore, the temperatures measured represent the average temperature rather than the peak temperature at the interfaces.
From the above evidence, it seems that melting is probably not necessary for the formation of a solid state bond, although melting may occur locally under conditions of high power input and long weld time.
<table>
<thead>
<tr>
<th>Weld material</th>
<th>Melting point of lowest melting material $T_m$ (°K)</th>
<th>Maximum observed $T$ (°K)</th>
<th>$T/T_m$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (ultrasonic weld)</td>
<td>933</td>
<td>644</td>
<td>69%</td>
<td>41</td>
</tr>
<tr>
<td>Aluminum (ultrasonic weld)</td>
<td>933</td>
<td>610</td>
<td>65%</td>
<td>11</td>
</tr>
<tr>
<td>Gold (ultrasonic weld)</td>
<td>1336</td>
<td>333</td>
<td>25%</td>
<td>10</td>
</tr>
<tr>
<td>Al-Au (ultrasonic weld)</td>
<td>933</td>
<td>338</td>
<td>36%</td>
<td>10</td>
</tr>
<tr>
<td>Cu-Monel (ultrasonic weld)</td>
<td>1356</td>
<td>503</td>
<td>37%</td>
<td>8</td>
</tr>
<tr>
<td>Iron-nickel (friction weld)</td>
<td>1726</td>
<td>1673</td>
<td>96%</td>
<td>65</td>
</tr>
<tr>
<td>Aluminum-nickel (friction weld)</td>
<td>933</td>
<td>693</td>
<td>74%</td>
<td>65</td>
</tr>
<tr>
<td>Nickel-titanium (friction weld)</td>
<td>1726</td>
<td>1273</td>
<td>74%</td>
<td>65</td>
</tr>
<tr>
<td>Aluminum-titanium (friction weld)</td>
<td>933</td>
<td>673</td>
<td>72%</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 4.2 Bonding area temperature measured in some solid state welds
4.3.2. Diffusion

Diffusion is a thermally activated process related to the material properties and applied temperature and time. For one-dimensional planar diffusion, the time dependence of diffusion distance obeys a simple relation as following:

\[ X = C (D t)^{1/2} \]  

(4.1)

where \( X \) is the diffusion distance, \( D \) is diffusivity of the material, \( C \) is constant, and \( t \) is time. The diffusivity of materials has a complex relation with temperature, pressure, and deformation conditions within the materials. Experimentally, the temperature dependence of the diffusivity \( D \) in a single-phase system is invariably found to obey a simple relation:

\[ D = D_0 e^{Q/RT} \]  

(4.2)

in which, the ‘frequency factor’ \( D_0 \) and ‘activation energy’ \( Q \) are temperature independent, \( R \) is gas constant and \( T \) is absolute temperature. However, the influences of pressure and deformation on the diffusivity can not be described by a simple equation. Generally, higher static pressure may reduce the diffusivity of the material while dynamic pressure, such as explosive impact, may increase the diffusivity by invoking more defects in the structure [5]. The possibility of diffusivity enhancement by strain and strain rate may be related to the generation and migration of excess point defects during the deformation.
Diffusion is known as the dominant mechanism in diffusion welding [21,22]. Fig.4.4 shows a widely accepted sequence of metallurgical stages in diffusion bonding, from which we can see that grain boundary and volume diffusion play an important role in the bond formation [6]. Therefore, in order to accelerate the diffusion process and to get the required diffusion depth, diffusion welding is obtained at elevated temperatures and through longer welding time. Furthermore, since hot rolling is also operated at elevated temperature, diffusion layers have also been found in hot rolling laminates [23,24].

In other solid state welding processes, such as ultrasonic, friction and explosive welding, things become much more complex with respect to diffusion mechanism. Because on one hand, all the processes have extensive localized heating and plastic deformation along the interfaces, which could promote the interdiffusion process. However, on the other hand, the welding processes are fast and involve more complex metallurgical reactions along the metal interfaces, which bring doubts about the interdiffusion mechanism [5]. Therefore, although some investigators have shown evidence of interdiffusion layers in all these processes [25,26,28,12], many researchers have also claimed that no interdiffusion layers were detected in either of ultrasonic, friction or explosive welding processes [16,27,29].
4.3.3. Recrystallization

It has been reported that intimate contact between two mating surfaces can be achieved by means of a recrystallization process due to the migration of grain boundaries [30]. The evidence for recrystallization based on metallographic observations on the interfaces of ultrasonic, friction and explosive welded joints of various metals has been shown by many researchers [31,16,33].

In the ultrasonic welding process, Okada [31] reported that the temperature rise in the bonding area is higher than the recrystallization temperature of the materials used. He provided further evidence for recrystallization by means of X-ray diffraction patterns. However, based on cross-sectional metallography, Joshi [10] reported that no sign of recrystallization occurred in the bonding areas of Au-Au, Al-Al, and Au-Al ultrasonic welds. In addition, Noltingk [32] reported that there was no evidence of recrystallization in aluminum welds using micrographic observation.

Recrystallization phenomena in friction and explosive welding process have also been observed by several investigators. During linear friction welding between Ti-6242S and Ti-14-21, Baeslack III et al [33] reported fine beta grain structure(25μm) at the weld interface. They claimed that this fine structure was the result of dynamic recrystallization during the welding process. Similarly, in the explosive welding of steels, Lucas and Crossland [16] observed recrystallization of the ferrite surrounding the martensite pocket.
The martensite pocket formation was believed to be the result of rapid cooling of melted vortices during explosive welding.

Based on the available evidence, it seems that recrystallization will not necessarily occur during ultrasonic welding. However, there is a higher probability for recrystallization to occur in friction and explosive welding because of the higher temperature ranges involved in both processes.

4.3.4. Adhesion

Adhesion resulting from atomic attraction has been widely accepted as the basic bonding mechanism for all kinds of solid state bonding techniques [25,34,35]. As we all know from atomic attraction theory, the atomic attraction force between two atoms reaches a maximum at an interatomic distance of several angstroms (for example, the attraction force between copper atoms reaches a maximum at an atomic distance of 3.5 angstroms), and it is proportional to the inverse of the square of the atomic distance. Therefore, in order to obtain atomic adhesion, two clean surfaces to be welded must be brought to within a distance of 10 angstroms [5]. This condition has been achieved in solid state bonding by applying adequate pressure and deformation. Generally, for clean metals at room temperature, a normal pressure sufficient to give a reduction in thickness of ~10% is all that is needed to give intimate contact of two metallic surfaces [5]. Unfortunately, such pressures and deformations are not sufficient to give welding in most metals at room
temperature because it is difficult to break-up the oxide film on metals with such small deformation.

In diffusion bonding, surface cleaning is very important in order to bring two mating surfaces into intimate contact because the deformation in diffusion bonding is too small to break up and disperse the oxide films on the metals except for some high interstitial solubility metals [21,36]. In roll bonding, high surface extension is needed to break-up and disperse the oxide films and bring nascent metals together to form a strong bond. However, during roll bonding, materials are under hydrodynamic pressure, even oxide films are dispersed, they can not be completely eliminated from the interfaces [35]. Therefore, the existence of oxide films will decrease the contact area between nascent surfaces. Appropriate surface cleaning is also important prior to roll bonding and the time between cleaning and welding must be maintained as short as possible.

In ultrasonic and friction welding, many researchers have reported that surface cleaning has no significant influence on the bonding strength [11,37,25,29,19]. The explanation was that in both processes, the high frequency rubbing between two surfaces prior to joining has a significant effect of breaking up the oxide films and even extruding them out of the joining interfaces. They believed that adhesion produced by plastic deformation is the most important mechanism for ultrasonic and friction welding processes. In addition, in explosive welding, the metallic jetting (a hydrodynamic flow of metal surfaces upon collision) ahead of the collision points between two mating surfaces has
been widely accepted as the main medium of extruding the contaminant away from the weld interfaces, and the intimate contact of two clean surfaces is believed to be the primary mechanism in explosive welding [13,14,16].

However, instead of using the term “atomic attraction”, other researchers used the term ‘mechanical interlocking” to refer to the bonding mechanism for dissimilar solid state welds [10,33,34,39]. However, these authors did not clearly define the underlying operation of mechanical interlocking which was supposed to be the cause for bond formation in dissimilar welds. The term “mechanical interlocking” was mainly used to describe the appearance of turbulent and disrupted interfaces in dissimilar welds as compared with the relative smooth interfaces in similar welds. For example, a liquid like flow of gold whirling around a copper surfaces in an Au-Cu weld has been represented as a typical feature of interlocking [34].

Therefore, as a descriptive term, mechanical interlocking cannot be considered as an explanatory concept for bonding formation in dissimilar welds. It seems that it is reasonable to believe that the bonding mechanisms for similar and dissimilar welds are the same. The difference in the interfacial appearance between similar and dissimilar welds may be mainly due to the differences in the mechanical and physical properties of the weld materials involved.
4.3.5. **Interfacial reaction**

The interfacial reaction in the solid state welding process can be classified into three categories: the reactions of oxide films with weld metals, the reactions between weld metals and phase transformations during welding processes.

Most metals react with atmospheric oxygen to produce oxide films which form a layer upon the metallic surface. Functioning as bonding barriers in solid state bonding, oxide films are usually very difficult to be completely removed before welding. Therefore, the solubility of the oxide in metal can play an important role in solid state bonding processes, especially in diffusion welding [5]. During deformation assisted solid state bonding, such as roll bonding, ultrasonic, friction and explosive welding, oxide films are generally believed to be fractured or effaced from the weld interfaces. For example, in the ultrasonic welding of colored anodized aluminum, Noltingk [32] showed the way in which the oxide film has been broken-up and reoriented in the welded specimen using micrographic examination. Similarly, Yilbas et al [20] reported that in the friction welding of aluminum, the oxide film has been broken into small compounds. Both of them have concluded that the existence of oxide film has no effect on the bonding strength. However, in diffusion controlled solid state bonding, oxide film can significantly increase the difficulty of bonding and reduce the bonding strength. Therefore, in order to solve this problem, both surface cleaning to remove oxide film and increasing temperature to increase the solubility of the oxide in metal are commonly used.
in diffusion welding process [21]. In addition, Kotani Keiko et al [39] have reported that adding an element with strong affinity to oxygen, like Mg, into the intermediate layer as well as the base metal can improve the bond strength of the joint interface, by changing the morphology of the interfacial oxide from amorphous film to crystalline particle. They verified this method by significantly improving the diffusion bond strength of pure aluminum using Al-Mg foil as an intermediate layer.

The reactions between weld metals usually result in the formation of intermetallic compounds at the interfaces. This has been reported in diffusion bonding, friction and explosive welding because of the higher temperature involved in these processes. For example, in the diffusion bonding of Al₂O₃ to Ti, Kilauga and Ferrante [40] detected the formation of Ti₃Al reaction layer using TEM imagine examination. They also did shear test to specimens bonded at 800 degree C and concluded that the crack always propagated within the Ti₃Al layer. Moreover, Lucas and Williams [16] have reported the intermetallic compound formation of aluminum to copper joining for both friction and explosive welding, but they did not mention the influence of the compounds on the mechanical properties of the joints. Generally, the formation of intermetallic compound has been believed to be harmful to the joint strength even though some researchers reported that maintaining the intermetallic compound layer below several micrometers thick could increase the joint strength [19].
Phase transformation is a heat-assisted process accompanied with the heating and cooling effect during the welding. Combined with phase diagrams, phase examination has been used to indicate the temperature range involved in the ultrasonic welding process [41]. However, because of the short welding time involved in the process, it is doubtful that the predicted temperature will reflect the real case in which non-equilibrium phase transformation has actually occurred [25].

From the above evidence, we can see that in order to get successful bonds, interfacial reaction can not be neglected. However, it is not the unique bonding mechanism in solid state welding because many good bonds have also been obtained without any interfacial reactions.

4.3.6. Interfacial morphology

Interfacial morphology has been regarded as a unique characteristic in explosive welding in the form of planar, wavy or molten layer interface. Most investigators believe that the wavy interface plays a vital role in the bond formation since it always yields the desired bonding properties [42,43,15]. In the explosive welding of aluminum and steel plates, Balakrishna [43] reported that the strength of bond produced by extreme metal deformation that result in a wavy interface was found to be maximum. Many other researchers had the similar observation that welding produced with the forming of stable wavy interface was least sensitive with respect to the collision condition fluctuations
during the welding process [12,15,17]. However, in the explosively welded Aluminum/Steel specimens, Szecket et al [44] found that the failure subject to tensile test for specimens with waveless interfaces was seen to occur in the aluminum, away from the weld interfaces, while for samples with wavy interfaces containing Fe-Al intermetallics, the tensile failure occurred at the weld interfaces. Additionally, the waveless interfaces were observed to be devoid of intermetallic formation and maintain integrity with heat exposures up to 8 hours at 550°C. Moreover, continuous molten or diffusion layer has also been reported to have good bond strength, if the layer thickness is within several micrometers and intermetallic compound does not play a significant role in determining the bond strength [16, 43]. Therefore, this interfacial phenomena can not be used alone to determine the quality of the bond. Even so, since the wavy interface is very common in practice and it will influence the final nature of the weldment, it is worthy to note the conditions affecting the wave formation.

The mechanism of wave formation has been studied qualitatively and quantitatively by many investigators. The qualitative study of wave formation was largely based on a serials of experiments conducted for a variety of metal combinations under different conditions. Typical work in this direction was done by Abrahamson [45] and Bahrani [46]. They both concluded that critical conditions (critical incident angle and impact velocity) existed for wave formation using particular operation equipment. Although Abrahamson made an initial attempt at describing the wave formation, the mechanism proposed by Behrani was more in accordance with experimental evidence [48]. However
it did not provide any quantitative framework in order to relate the explosive welding parameters to the wave formation and its periodicity. The quantitative study of wave formation was mostly based on the similarity between the interfacial waves in impact welding, and the waves observed in various fluid flow situations, such as those generated behind an obstacle in a uniform fluid flow or those formed at the interface of two fluid streams which have different velocities. Typical work of this kind was done by Cowan [47]. The proposed mechanism stated that the generation of waves in explosive welding depends on the velocity of the flyer plate relative to collision point and the collision angle, \( \theta \). Fig 4.5 shows the conditions for the transition from smooth to wavy interfaces (\( V_c \) is collision velocity). At low velocity boundary, the transition velocity is largely independent of \( \theta \) and the limit is mainly determined by the yield stress of the material. At high velocity boundary, as shown by the dashed line, the behavior becomes more complicated because of possible melting and extremely high pressure at the collision point.

The mechanism discussed above provides a general understanding about the wave phenomena, a more comprehensive review is available in the wave formation discussion by Crossland [48]. However, the wave mechanism is by no means of well established because of the complex nature of the explosive welding process that involves various physical phenomena such as explosion, high velocity collision of metals causing plastic deformation at large scale, and interatomic bonding at the interface at much smaller scale under the conditions of high pressures accompanied by temperature rise and all this
occurs in a very short duration of time. Fortunately, though the problem of wave formation mechanism is an intriguing one, nevertheless its solution is not essential to the practical application of the explosive welding technique.

4.3.7. Summary

After reviewing the various bonding mechanisms and important metallurgical phenomena for various solid state bonding techniques, it appears that these mechanisms can be classified into two categories. The mechanisms of melting, diffusion, recrystallization and interfacial reaction are based on a heat–assisted process. The high interfacial temperature between the bonding surfaces is considered to be essential to the bond formation. The other mechanism, adhesion, considers the interfacial temperature rise to be a by-product of welding process. It attributes the bonding formation to a solid state process accomplished by atomic attraction through plastic deformation.

Considering the relative importance of existing mechanisms proposed by different investigators, it can be seen from the literature that most investigators have attributed the bond formation to more than one mechanism. A majority of investigators believed that adhesion is the major mechanism causing the bond formation, while only a limited number of authors suggested melting as the primary mechanism. The other mechanisms, diffusion, recrystallization, and interfacial reaction are generally considered as secondary factors for bonding formation.
4.4. Finite Element simulation of the solid state welding process

From the description of various solid state welding techniques and the comprehensive study of the solid state bonding mechanisms, we can see that solid state bonding is a complicated research area involving different aspects in mechanics, thermal and material science. The extensive knowledge in this complicated area is not easily obtained as a variety of experimental setups and the complicated dynamic interaction between different phenomena in the welding process is extremely difficult to describe in a closed analytical form. Therefore it may seem that computer modeling of the welding process is a useful approach for a better insight into the mechanism of bond formation at the interfaces and further provides design and quality control information.

4.4.1. Modeling attempts for different solid state welding techniques

The numerical study of solid state bonding can be divided into two broad categories: diffusion controlled or deformation controlled bonding. Diffusion controlled mechanism refers to solid state bonding under low pressure, high vacuum and high temperature conditions, such as diffusion bonding. Deformation controlled bonding refers to the solid state bonding processes in which the material deformation plays an important role in achieving a sound bond, for example, ultrasonic welding. Although there is limited information about the numerical study of these solid state bonding processes from the
literatures searched, some of them may have important clues for our further study. Therefore, it is worthy to discuss some of the results done by various investigators.

In the first category, simulation has usually been focused on interfacial regions. The interfaces are considered to be irregular with hills and valleys. When the interfacial peaks are in contact, bonding area starts to grow as a void shrinkage process. The growth rate of the bonding area is controlled by several mechanisms: plastic flow, creep deformation, interface and volume diffusion. A typical model of this kind was done by Yasuo Takahashi and Kimiyuki Nishiguchi [49]. Based on the numerical model, they built up the criterion for optimum bonding related to time, temperature and pressure. The predicted bonding condition was verified by experimental study. Following the idea of an uneven interface, they further enhanced their model by relating the interfacial region with the bulk material using finite element method [50]. The deformation after initial contact was treated as viscoplastic and the interfacial deformation was guaranteed by remeshing technique. However, they neglected the diffusion process in this finite element model, which actually plays an important role for bonding under high temperature and long welding time conditions. Therefore, their model should only work for high compressive conditions which may inhibit the diffusion process. Another problem in this model was that the interfaces were considered to be free from oxide films, which however should be present for most solid state bonding processes. One simulation model proposed by C.S.Lee, H.Li and R.S.Chandel [51] solved this problem by treating the dispersed oxide as particles in the matrix. Considering the relative deformation of the particles and matrix,
they concluded that after bonding the interface should be free of oxide particles. However, the simulation model was only based on qualitative explanations. No quantitative equations or numerical results are available to sustain the proposed model.

For deformation assisted bonding, varieties of simulations have been done based on different phenomena in the bonding processes. The most widely studied area is the temperature distribution during the friction welding process. As mentioned before, friction welding is accomplished in three main stages, namely initial, friction and forging stage. The temperature distribution after the first two stages (right before the forging starts) is crucial for obtaining sound welds during the forging stage. In addition, generally it is believed that no metallurgical bonding occurred during the heating process. Therefore, it is simply a coupled mechanical-thermal analysis, which is relatively easy to model using finite element method. Several researchers have proposed simulation results of the heating stage for different friction welding processes (continuous drive friction welding, inertia friction welding and linear friction welding) either by coding or using commercial codes [52,53,54], they obtained good agreement between simulation and experimental results. However, when the modeling comes to the forging stage, difficulties arise because in the forging stage, the deformation is large, materials behave differently from those under normal conditions and metallurgical interactions are also involved in most welding processes. Therefore, appropriate assumptions must be made to successfully model the final stage. The first attempt to theoretically describe the forging stage in friction welding was done by Rich and Robert in 1971 [55] using a plasticity material model. Following this theoretical description, a complete finite element
modeling of the whole friction welding process was proposed by Andrzej Sluzalec in 1990 [56]. In his model, an elastic plastic material with thermal softening effect and a finite element technique so called incremental approach were used to treat material behavior and large deformations in the welding process. However, rate dependent plasticity was neglected in the model and no bonding criterion could be established from the simulation results. Another complete finite element model for inertia friction welding was proposed by A.Moval and E. Massoni [57] in 1995. In their model, a temperature dependent viscoplastic material model and adaptive remeshing technique were used to deal with material behavior and large deformations. Although their model could predict the final deformation shape and temperature distribution very well, it could not provide a specific criterion for bonding. One important aspect needed to mention here is that for all the finite element models discussed above, the friction law was predicted either by experimental study or empirical estimation.

For modeling in ultrasonic welding, only one paper has been encountered by the author. The paper was written by Gerdes Ron et al [58]. In their study, they performed finite element analysis on the parts before welding to extract their natural frequencies. Then the ultrasonic vibration frequency should be away from those frequencies to avoid large deflections of the parts during welding. Strictly speaking, it is not a model for ultrasonic welding, but it can provide useful information for choosing welding parameters.
In the modeling of explosive welding, two approaches have been commonly used by most researchers. One is modeling the explosive welding as a complete thermal mechanical analysis, the other is focusing on the mechanism of wave formation in the welding. In 1984, Oberg, schweitz and Olfsson [59] proposed a finite difference model to simulate the process at all scales of the problem, which include a large scale involving impact of the two plates resulting in deformation patterns, velocity fields, pressures, temperatures etc. and a smaller scale where phenomena such as jet formation are simulated. The computational work in this paper uses a Lagrangian finite difference technique to study mainly the hump and jet formation for various steel, aluminum and copper combinations. However, the work could not investigate the wave generation because of limitations of the technique such as, excessive mesh distortion at the interface. In order to avoid the mesh distortion problem, Hermant [60] used a finite element code AUTODYNE with Smooth Particle Hydrocode (SPH) solver (no physical mesh is required) to simulate the explosive welding process. Even though the SPH solver has some limitations, such as friction can not be included, nice distributions of temperature and strain at the interface were obtained through the simulation. Additionally, the transition conditions from planar interface to wavy interface obtained from the simulation were in good agreement with the experimental work done by Botros and Groves [61].

Therefore, from the previous work discussed above, we can see that computer modeling offers great opportunity for our researchers to understand and design the solid state bonding process faster and easier. However, problems such as treating the material
behavior under extreme conditions and the metallurgical bonding using numerical techniques need to be further improved to obtain better agreement between simulation and experimental results.

4.4.2. Available software for our solid state welding simulation

Solid state welding is a complex physical process whose realistic modeling requires a numerical tool with at least the following features:

- Thermal – Mechanical coupling. In the welding process, work done due to friction and plasticity on the mechanical side of the analysis affects the temperature field. Following the data from the mechanical analysis, the updated temperatures will account for the stress and strain calculations.

- Material non-linearity. Material properties have significant influence on the accuracy of the prediction. Temperature and rate dependent material properties are required for accurate representation of the process.

- Complex thermal and mechanical boundary conditions. This includes conduction of heat from the sliding interface to the bulk material and complex contact conditions between the interfaces.

- Remeshing technique. The large deformation in the welding process usually causes excessive mesh distortion and tangling. In order to study the interfacial morphology, efficient remeshing technique must be required.
The available softwares including all the above features in the Ohio State University are ABAQUS and LS_DYNA. Both of them are finite element codes. ABAQUS was developed by Hibbitt, Karlsson & Sorensen Inc, LS-DYNA was developed by Lawrence Livermore National Laboratory.

Another software available in Glenn S. Daehn’s group is AUTODYNE developed by Century Dynamics Corporation. It is a nonlinear dynamic finite element code capable of solving variety of impact structure analysis. It also has a SPH solver which is proved to be able to simulate complex interface morphology during impact welding [60].
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Figure 4.1  Fundamental steps in friction welding process
Fig 4.2  Explosive welding set up and bonding configuration
Fig. 4.3  Typical components of an ultrasonic welding system
Fig 4.4 Sequence of metallurgical stages in diffusion bonding process. (a) Initial contact. (b) Deformation of surface asperities. (c) Grain boundary diffusion of atoms to the voids and grain boundary migration. (d) Volume diffusion of atoms to the voids.
Figure 4.5  Theoretical boundaries of wave formation for collisions (a) of flat streams of Newtonian liquids, and (b) of flat plates of elastic-plastic solids. (c) Typical observed boundary of wavy bond zone in metal cladding
CHAPTER 5

5. HIGH SPEED SPOT IMPACT WELDING

5.1. Introduction

Aluminum is one of the world’s most versatile materials. Its application characteristics include: corrosion resistance, low density, strength, and durability. As the automotive industry strives to produce safer, lighter, more fuel-efficient automobiles with ever increasing options, manufacturers have begun to use aluminum intensively. A major challenge is how to design the automobile in such a way to maximize the advantages and minimize the disadvantages. The space frame design and the unibody are two competing possibilities. The space frame uses a network of metal rails for the frame that are covered by a thin skin body. The unibody depends on the joining of the automobile’s body panels to form a stiff shell structure [1]. A key element in the success of either design is the production robustness and properties from joints from the available joining technology. Currently in use are such techniques as spot welding, rivets, TIG welding, adhesives or a combination of these techniques. Another option in the joining
technology menu – Spot Impact Welding has been developed in our group. During the ‘Spot Impact Welding’ process, a high velocity projectile strikes two adjacent sheets of metal and forces them into a die. If the conditions are proper, a true metallurgical bond joins the two sheets. Strengths comparable with spot clinching [2] and spot welding [3] have been attained without some of their inherent drawbacks. The process is very flexible, having bonded aluminum alloys (6111-T4, 6022-T4, and 5754) using four different projectile materials (lead, PVC, 1100 Al, and copper coated Al) and several different projectile shapes. The process also offers the promise of being able to join dissimilar materials, and dissimilar materials thickness. Spot Impact Welding has the promise of being able to inexpensively join and may be much more versatile than other joining methods. With its simple setup, the process could be very easily adapted to the automotive and aerospace industry. The portability of the required equipment also makes this process well adapted to construction and field repairs. This outlines the potential of this method and it shows the path we are taking to develop the method.

5.2. Background

In general, Solid-State welding (SSW) processes join surfaces at temperatures below the melting point of either work piece and without the addition of filler materials. This bonding technique is usually classified into two broad categories: diffusion bonding without a large amount of plastic deformation; and bonding accompanied by extensive plastic deformation, such as roll bonding and friction welding. Both categories have
specific techniques regarding the difference in energy supply, temperature range and bonding time duration [4].

Currently, several solid-state welding techniques are being widely used in industry, in techniques such as explosive welding, ultrasonic welding, diffusion bonding, friction welding and roll bonding. Among them, friction and welding diffusion bonding involve higher temperature ranges. Roll bonding requires extensive plastic strains. In addition, each of them has different limitations on specimen geometries and sizes. [6].

Clinching is a mechanical joining process that does not create a metallurgical bond between the materials. Owing to its low cost and flexibility, this mechanical press joining by local cold forming finds extensive applications by complementing or replacing spot welding joints. [7] This technique has limitations with joining high strength materials, as large plastic strains are required to make a joint. This can cause tearing of the sheet [7,8].

Work performed at Ohio State [9,10] and elsewhere [11,12] over the past several years has shown that at high velocities material formability can often be dramatically improved. Also high velocity deformation can dramatically reduce springback and can produce natural interference fits. For these reasons, we thought it may be interesting to attempt to develop a high velocity spot clinching process. We were happily surprised that we stumbled upon a process for creating solid-state metallurgical joints instead.
5.3. Spot impact welding setup

Our initial investigation was to try to reproduce a clinch joint with an apparatus like that in Fig. 5.1 by impacting two thin sheets with projectiles forcing it into a die with geometry similar to that shown in Fig. 5.2. During this process we discovered that as we increased the velocity to a certain value, the sheets were very difficult to separate. When the sheets were finally separated, we discovered that a part of the first sheet was still stuck to the second sheet and in fact had developed a metallurgical bond, and there was no interference fit.

5.3.1. Setup I

Our initial studies used a 3000-psi, 9mm commercial air rifle mounted horizontally on a basic L-frame of extruded aluminum tubing (Fig. 5.1). This propelled a projectile to impact 2 thin aluminum disks (50mm in diameter x 0.92 mm thick) against a shaped die. The breach was mounted to a double shaft mounting plate using a bolt through the scope mount, while the muzzle was located in a machined hole of a stanchion cross clamp. The velocity of the projectile was measured using an Oehler Model 35 Proof Chronograph that utilizes 3 screens, 2 timers. Each skycreen has a photoelectric eye with a crystal oscillator frequency of 4 MHz for a 0.25 microsecond time resolution. With this system
two independent estimates of velocity are given and they typically vary by 0.3 meter per second or less.

In this investigation, two sheets of aluminum were mounted flush in front of the die using a mounting clamp and a 3.78-gram soft lead bullet was used to generate the deformation via impact. With this system the bullet can attain velocities up to about 370 m/s and controlling the air pressure in the gun can vary the projectile velocity. The cross section of the hardened steel die used to shape the deformed region is shown in Figure 5.2. Pin variations consisted of: four different outer diameters D (8, 9, 10, and 12 mm), three different tab diameters d (4.5, 5, and 6 mm), and two different tab heights h (1 and 1.5 mm). The die was lubricated with light oil (WD-40) to keep the aluminum from bonding to the steel die, which was sometimes a problem. The die was mounted in a 2-axis micrometer mounted vise that allowed alignment of the bullet path to the approximate center of the die (with about 2-3 mm of scatter). The die was positioned within a Lexon safety cage. The surfaces of the target disks were cleaned with soap and water and then placed in an ultrasonic cleaning bath of Buehler Ultramet sonic cleaning solution.

5.3.2. Setup II

There were two important limitations of the first test setup. First, the kinetic energy of the projectile was somewhat limited. We envisioned many situations where higher energy
projectiles would be required. Second, the relatively long flight distance for the projectile (which allowed the velocity of every shot to be measured) creates 1-3 mm of shot to shot scatter in impact location. This manifested itself in scatter in the weld strengths.

These two issues were remedied with a second-generation setup. A .357-inch Thompson Centerfire pistol (Fig. 5.3) was mounted vertically to an aluminum and polycarbonate box and used to propel a projectile to impact two thin disks against the die from Fig. 5.2. The pistol was held firm in a machined fixture by casting its barrel in urethane resin and mounting it atop the box. Another machined fixture, bolted to the bottom of the box and centered with positioning screws, located the shaped die with a receiving hole. Between the pistol mount and the adjustable die mount, shot to shot off-target scatter was negligible. Projectile velocity was controlled by the amount of powder charge and calibrated in separate experiments via the skyscreen chronograph. Mounting the disks and impact are the same as in setup I with the exception of the amount of energy available. By using an 8.04-gram copper coated lead hollow point projectile and varying the powder charge, the range of velocities is greatly increased. Even with this relatively massive projectile, velocities over 300 m/s are easily attainable.
5.4. Bonding characteristics and strength

The bonding experiments were done in two stages. At the first stage, a set of test samples were placed against a Die/Pin set with 9.8mm D, 4mm d, and 1.5mm h and tested with different energy levels. Then, the testing samples were cross-sectioned to view the bonding characteristics for further development. At stage two, combining with the results in the first stage and finite element modeling, another set of samples were tested through a matrix of pin and die geometries as shown in table 5.1 using both setup I and II. Then, the specimens were collected for cross-section metallographic examination and strength tests.

<table>
<thead>
<tr>
<th>Die</th>
<th>Pin</th>
<th>Pin Dia (D) mm</th>
<th>Tab Dia (d) mm</th>
<th>Tab Height (h) mm</th>
<th>Inlet Rad (R) mm</th>
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<td>A</td>
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<td>9</td>
<td>6</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>9</td>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>9</td>
<td>4.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>A</td>
<td>10</td>
<td>5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>10</td>
<td>6</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>10</td>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>10</td>
<td>4.5</td>
<td>1</td>
<td>1</td>
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<td>6</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>12</td>
<td>5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>12</td>
<td>4.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>12</td>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1  Die/Pin geometry matrix for experimental testing
5.4.1. Bonding characteristics

Figure 5.4 shows some of our very first tested samples with close view of the obverse and reverse side of bonded tab area. Primary examination of the collected samples was done using optical microscopes. Specimens were first cut in two and each half section was then mounted and polished before examination. Figure 5.5 shows two 6111-T4 bonded samples at different impact velocities. Each bonded specimen welded around the diameter of the pin tab and in a few instances around the die inlet radius.

The large welding regions in both samples in figure 5.5 show promising results of the first setup and weld configurations. However, it also revealed a limit condition in the design. At 256 m/s projectile impact velocity, the specimen on the right can be seen to exhibit more deformation and bonding area than the one on the left at 211m/s. Larger bonding area will result in higher bonding strength. On the other hand, the specimen on the right can be seen to exhibit more thinning and crack than the one on the left with lower impact velocity. Thinning would later prove to be the major cause of failure in the bonded specimen. As seen in both pictures in figure 5.6, the thinning was the greatest around tab diameter and some around the die inlet radius. Figure 5.6 shows an extreme case of tab diameter and die inlet radius thinning.
The second-generation die/pin set as shown in table 5.1 was completed and along with setup II bonded specimens from testing were sectioned in the same manner as above. As in previous examinations, strong welds were discovered around the tab diameter. Unlike previous examinations, however, a dramatic reduction in thinning was noted. Throughout the entire length of the specimen, both sheets were thinned to roughly an equal amount as seen in Figure 5.7. Gone was the dramatic thinning at the inlet radius to the die, which had caused large deformation in previous experiments. The thinning at the tab diameter was still a problem, although to a lesser extent.

5.4.2. Bonding probabilities

Using the first-generation die (10mm diameter die with 2.7mm pin depth) along with setup I, 145 samples were first examined to study the bonding probability. 3.78-gram lead bullets were shot onto the aluminum 6111-T4 sheets at velocities varying between 150m/s and 300m/s. In these 145 samples, 134 of them have two aluminum sheets welded together. The bonding probability was as high as 92% disregarding the bonding strength. The specimens were not welded either because the aluminum sheet were hit at too high velocities (>270m/s) or too low velocities (<170m/s). In the second-generation die/pin set showing in table 5.1, a large number of tests have been performed for different die/pin geometries, sheet surface finish and material combinations along with different types of projectiles. The resulting bonding probability varied a lot upon the above factors. This will be discussed in detail in later sections.
5.4.3. **Strength**

Bonded specimens that were not cross-sectioned and examined optically were used to determine the strength of the joint. To fully characterize the strength of the joint, bonded disks were installed in a MTS model 810 and joint strength was measured. Samples were tested in three different modes: peel, shear, and tensile. Standard grips were used for the peel and shear tests, while a machined fixture was used for the tensile tests that allowed for pin loading. Dependent on the impact velocity, the following strength ranges were obtained: peel test (0.1-.5 kN), tensile test (0.2-1.0 kN), and shear test (1.0-4.0 kN). When the samples failed, it was typically due to thinning of the impacted disk along the radius of the pin tab as seen in Figure 5.6.

5.5. **Factors affecting bonding**

Numerous parameters had a large impact on the spot impact welding process. Control of these parameters influenced bonding characteristics and strength even whether or not the target disks bonded at all. During experimental processes, bullet velocity (impact energy), setup geometry, choice of bullet, surface finish of the sheet metals and even different material combinations were considered with respect to optimizing bonding parameters.
5.5.1. Influence of energy

Projectile kinetic energy was the direct source of energy that went into bonding. In order to get a strong solid-state weld, the sheets to be welded must have sufficient plastic deformation to rupture oxide films and obtain extremely close contact through the bonding interfaces, within the range of mutually attractive forces. This was controlled by the bullet mass and velocity during the experiments. For a majority of the experiments in setup I, a 3.78-gram lead bullet was used to impact aluminum sheet metal. When the bullet velocity was too low, the two sheet metals were deformed to dimple shape and could be separated apart easily after impact. When the bullet velocity was too high, the two sheet metals were torn and cracks were formed. Good bonding and finishing only could be obtained in a proper amount of energy. Figure 5.8 shows deformed sheet metal impacted at three different energy levels.

Using setup I and a 3.78-gram lead bullet for first generation 10mm diameter die and 2.7mm pin depth, the velocity range for bonding to occur was observed to be within 170m/s and 270m/s. For second-generation die/pin combinations, bonding was observed for 12mm diameter die, pin geometry A with 3mm pin depth at bullet velocity of 280m/s. But for stable results, bullet velocity lower than 270m/s was preferred.
5.5.2. Die/pin geometry

The die/pin geometry influence on the bonding characteristic was carefully studied using both finite element simulation and experiments. Table 5.1 summarizes all the geometry combinations used in the study. These combinations were studied for sheet metal aluminum 6111-T4 impacting on aluminum 6111-T4. When using 8mm diameter die, pin geometry A was tested with pin depth varied from 1.5mm to 2.5mm, bullet velocity varied from 200m/s to 270m/s. Only 2 out of 20 cases (10%) did bonding occur. When the die diameter increased to 10mm while keeping other factors, 12 out of 20 cases (60%) were successfully bonded. When the die diameter increased to 12mm, using both pin geometry A and B, 18 out of 20 cases (90%) were bonded. In addition, die diameter larger than 12 mm, for example, 13mm, were tested for 5 cases, three of them were bonded, but the bonding quality was not strong. Therefore, die diameter 10mm and 12mm was selected along with corresponding pin A, B, C, D for further study for aluminum 6111-T4. Table 5.2 summarizes the results of the testing.

<table>
<thead>
<tr>
<th>Die (D in mm)</th>
<th>pin</th>
<th>Depth(mm)</th>
<th>Velocity(m/s)</th>
<th>Shear strength (kN)</th>
<th>Bonding probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>A</td>
<td>2.5</td>
<td>166-265</td>
<td>0.487-2.096</td>
<td>22/28 (78%)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2.5</td>
<td>194-251</td>
<td>1.207-2.354</td>
<td>8/12 (67%)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2.5</td>
<td>198-215</td>
<td>1.57-2.378</td>
<td>2/9 (22%)</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>2.5</td>
<td>193-212</td>
<td>1.018-1.29</td>
<td>4/10 (40%)</td>
</tr>
<tr>
<td>12</td>
<td>A</td>
<td>2.5</td>
<td>203-267</td>
<td>0.384-1.631</td>
<td>8/10 (80%)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2.5</td>
<td>193-274</td>
<td>0.394-3.77</td>
<td>7/8 (87.5%)</td>
</tr>
</tbody>
</table>

Table 5.2  Testing results for setup I using 3.78-gram lead projectile
In viewing table 5.2, the die/pin combination 12B has the best results. It gave a bonding probability of more than 87% and joint shear strength as high as 3.77kN while most other combinations have much lower bonding probability and lower bonding strength. Additionally, 12B was also tested for aluminum 6022-T4. The results gave a bonding probability of 89% and bonding shear strength as high as 1.88kN. Therefore, 12B was decided as the optimized geometry within the range of testing and its cross-sectional view is shown in figure 5.9.

5.5.3. Projectile shape and material

Both the projectile nose morphologies and overall geometries will influence patterns of metal flow during deformation processes, hence the bonding. Three different projectile morphologies were used in testing: conical, spherical, and hollow-ended (figure5.10 a-f).

With the three shapes chosen, each was able to effectively bond two thin aluminum sheets, although to varying strengths. The spherical nose was used on two separate projectiles: soft lead (Fig. 5.10a) and lead/antimony (Fig.5.10e). Excellent results were obtained from the conical soft lead (shear strengths of .5-3.8 kN), but the conical lead/antimony with its sharp nose curvature ripped through the target sheets or excessively thinned them, resulting in no bond. A conical nose was machined onto three
different projectiles: 1100 aluminum (Fig. 5.10 b), UHMWPE (Fig. 5.10 c), and PVC (Fig. 5.10 d). The aluminum projectile showed definite welding (shear strengths of 0.21 to 1.21 kN), the UHMWPE projectile partially disintegrated upon contact and little deformation occurred let alone bonding, the PVC projectile showed some signs of bonding, but the bond was very weak (< .5 kN). The hollow-ended projectile (Fig. 5.10 f) was purchased commercially and consisted of a lead base with a copper coating. It produced solid welds and strengths ranging from .4 to 2.4 kN. Cross-sections of the successfully welded specimens demonstrated welding from the mid-point of the tab diameter to the top of the tab.

The majority of the projectiles used had a cylindrical body beyond the taper of the nose profile. The one exception was the soft lead projectile (Fig. 5.10 a), which had a hollowed out central section beginning from the rear, similar to the projectiles seen in Figure 5.11. This projectile shape resulted in a post-impact shape seen in Figure 5.12. The projectile mass in figure 5.12 was increased to 7.51 grams to highlight this phenomenon in more detail. The 3.78-gram projectiles used in actual testing behaved in a similar manner. The direction of material flow in the figure starts with die contact: the front of the projectile is quickly pushed into the die; the thin walls of the projectile body are then pushed into the die forcing the material to flow up the pin tab leaving this final distinctive shape. This is believed to help promote relative sliding between the two sheets, leading to welding.
No bonding was observed when more massive projectiles of the same shape were used; leading us to believe there is a fine line for bonding with this shape. Although this hollowed shape was the most effective, other shapes did produce bonds of lesser strength including PVC, 1100 aluminum, and lead/copper. Figure 5.13 (a-f) shows the post-impact of each of the projectiles used.

5.5.4. Different sheet materials

A wide variety of target materials were used to establish as large a window of material bonding as possible, although the main focus was clearly on aluminum and its alloys. Table 5.3 summarizes all the material combinations tested.

<table>
<thead>
<tr>
<th>Material #1</th>
<th>Material #2</th>
<th>Thickness (mm)</th>
<th>Test setup used</th>
<th>Velocity range (m/s)</th>
<th>Shear strength (kN)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>6111-T4</td>
<td>6111-T4</td>
<td>0.92/0.92</td>
<td>I &amp; II</td>
<td>166-280</td>
<td>0.38-3.77</td>
<td>bond</td>
</tr>
<tr>
<td>6022-T4</td>
<td>6022-T4</td>
<td>0.92/0.92</td>
<td>I &amp; II</td>
<td>213-277</td>
<td>0.65-1.88</td>
<td>bond</td>
</tr>
<tr>
<td>Copper</td>
<td>6111-T4</td>
<td>0.4/0.92</td>
<td>I &amp; II</td>
<td>184-231</td>
<td></td>
<td>No bond</td>
</tr>
<tr>
<td>ADQ steel</td>
<td>6111-T4</td>
<td>0.92/0.92</td>
<td>I &amp; II</td>
<td>280-324</td>
<td></td>
<td>No bond</td>
</tr>
<tr>
<td>5754 Al</td>
<td>5754</td>
<td>1.1/1.1</td>
<td>I</td>
<td>227-291</td>
<td>2.24-2.96</td>
<td>8/20 bond</td>
</tr>
<tr>
<td>6111-T6</td>
<td>6111-T4</td>
<td>0.92/0.92</td>
<td>II</td>
<td>227-266</td>
<td>0.46-1.79</td>
<td>7/9 bond</td>
</tr>
<tr>
<td>6111-T6</td>
<td>6111-T6</td>
<td>0.92/0.92</td>
<td>II</td>
<td>227-266</td>
<td>0.54-1.33</td>
<td>5/9 bond</td>
</tr>
<tr>
<td>Mg</td>
<td>Mg</td>
<td>1.49/1.49</td>
<td>II</td>
<td>241-266</td>
<td>0.893</td>
<td>1/2 bond</td>
</tr>
<tr>
<td>5386</td>
<td>6022-T4</td>
<td>0.76/0.92</td>
<td>II</td>
<td>241-266</td>
<td>0.31-0.75</td>
<td>10/15 bond</td>
</tr>
</tbody>
</table>

Table 5.3 Different material combinations tested in the experiments
As shown in table 5.3, dissimilar material bonding is very difficult to obtain in our experimental setup because of several reasons. First, the spot impact welding works in small areas by relative sliding of the two sheets to form solid state bonds. Second, the experimental setup wasn’t designed for dissimilar material bonding. As seen from previous discussion, the pattern of metal flow of each of the two sheets will significantly influence the results. During the welding of dissimilar material using high velocity projectile, the difference in material properties will influence the metal flow pattern, thus the bonding result. Therefore, without carefully design of the bonding process, it is very hard to control metal flows during dissimilar materials impact processes to achieve good bonding.

Two special cases in the above table need to be pointed out here. The 5754 aluminum was coated with a proprietary lubricating pretreatment before testing. After testing the pretreated samples through a variety of die and pin sets, good bonding was achieved using a 12 mm die and pin B at a depth of 2.5 mm with the 3.78-gram lead projectile. The samples were pulled apart in a test frame using the shear mode and good results were obtained as above. This testing especially shows good promise for bonding the aluminum samples with a pretreatment. Another set of interesting experiments was conducted with magnesium (1.49mm diameter). Target specimens of magnesium were cleaned with acetone and impacted with 3.78-gram lead projectiles into die/pin configuration 12/B

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using setup II. A standard pin depth of 2.5 mm was used. With the limited amount of magnesium available we were able to impact two specimens. Both examples completely filled the die cavity with one resulting in a bond. This in itself is rather remarkable because the Mg sheet material has less than 3% tensile ductility. The bonded specimen was then put through a shear test with a resultant strength of 0.893 kN. The joint failed through the solid-state bond as can be seen in Figure 5.14. The fact that very high strains were achieved (filling a 2.5 mm cavity) in addition to bonding was quite impressive considering the low ductility of magnesium.

5.5.5. Target Surface conditions

Several target surface conditions and/or lubricants were tested using both setup I and II. Surface condition refers to the state of cleanliness of the target surface prior to testing, whether it is as received, chemically cleaned, or lubricated. The cleanliness of the target sheets would give an idea of how robust our bonding process was and establish a gauge of what would be required from industry should they implement this process. The degree of cleanliness of the surface had a significant effect on the bonding process. Some of the initial as received 6111-T4 sheets were bonded, but this provided little information, as the true surface conditions were unknown, other than the fact that it had to be contaminated from shipping and storage. Aluminium sheet (6022-T4) received with visible oil on the surface would not bond and was therefore cleaned with soap and water followed by an ultrasonic bath in Ultramet Sonic Cleaning Solution for four
minutes. This cleaning step allowed the bonding process to occur with resultant shear strengths between 0.4 and 2.4 kN. The preceding two conditions were used for all testing with setup I and part of the testing with setup II. Another cleaning process used with setup II involved Acetone. A cotton ball was soaked in acetone and then swiped across the surface. This produced shear strengths of 0.54-1.33 kN for bonded samples of 6111-T6 and 0.46-1.79 kN for bonded samples of 6111-T6 and 6022-T4.

Lubricants were placed on the target surface to simulate industry conditions for press-worked sheet metal. Three different lubricants that were applied to aluminum 6022-T4 were studied: Franklin Oil Corp. (#7T), Oak International, Inc. (Oakdraw 777, #6P), and D.A. Stuart Co. (Drawsol #4L). Table 5.4 highlights the lubricant test matrix using test setup II. Each target specimen was first cleaned with Acetone and then coated with a light layer of oil prior to testing. In every instance, no bonding was observed despite varying the projectile velocity through a large range.
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Projectile</th>
<th>Target</th>
<th>Velocity Range (m/s)</th>
<th>Die/Pin</th>
<th>Pin Depth (mm)</th>
<th>Oil (#)</th>
<th>Bond?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Lead</td>
<td>6022-T4</td>
<td>253 ± 13</td>
<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Lead</td>
<td>6022-T4</td>
<td>253 ± 13</td>
<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Lead</td>
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<td>253 ± 13</td>
<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
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<td>6022-T4</td>
<td>288 ± 31</td>
<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>Lead</td>
<td>6022-T4</td>
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<td>12/B</td>
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<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>Lead</td>
<td>6022-T4</td>
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<td>12/B</td>
<td>2</td>
<td>7T</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
</tr>
<tr>
<td>12</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
</tr>
<tr>
<td>13</td>
<td>Lead</td>
<td>6022-T4</td>
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<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
</tr>
<tr>
<td>14</td>
<td>Lead</td>
<td>6022-T4</td>
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<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
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<td>253 ± 13</td>
<td>12/B</td>
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<td>6P</td>
<td>No</td>
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<tr>
<td>16</td>
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<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
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<td>Lead</td>
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<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
</tr>
<tr>
<td>18</td>
<td>Lead</td>
<td>6022-T4</td>
<td>288 ± 31</td>
<td>12/B</td>
<td>2</td>
<td>6P</td>
<td>No</td>
</tr>
<tr>
<td>19</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
</tr>
<tr>
<td>20</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
</tr>
<tr>
<td>21</td>
<td>Lead</td>
<td>6022-T4</td>
<td>236 ± 15</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
</tr>
<tr>
<td>22</td>
<td>Lead</td>
<td>6022-T4</td>
<td>253 ± 13</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
</tr>
<tr>
<td>23</td>
<td>Lead</td>
<td>6022-T4</td>
<td>253 ± 13</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
</tr>
<tr>
<td>24</td>
<td>Lead</td>
<td>6022-T4</td>
<td>253 ± 13</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
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<tr>
<td>25</td>
<td>Lead</td>
<td>6022-T4</td>
<td>288 ± 31</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
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<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
</tr>
<tr>
<td>27</td>
<td>Lead</td>
<td>6022-T4</td>
<td>288 ± 31</td>
<td>12/B</td>
<td>2</td>
<td>4L</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 5.4 Lubricant testing matrix
5.6. Finite element modeling of the spot impact welding

As the forgoing experimental description makes clear, spot impact welding has a wide multidimensional design space. Possible parameters that one may want to adjust in order to optimize the process include: projectile materials, projectile tip geometry, die geometry, projectile velocity die diameter. A very large experimental matrix is required to appropriately consider this design space. For this reason, it is desirable to use numerical modeling to help optimize this process.

Finite element simulations can reliably provide only the strain and stress distribution. Temperature variation and deformation process can be captured. It is not entirely clear what local criterion must be used to define if the metal sheets will or will not bond.

5.6.1. Simulation Procedure

The numerical simulation of the process was undertaken by ABAQUS, a finite element software developed by Hibbitt, Karlsson & Sorensen Inc, which includes all the features required for impact forming simulation.

Since the structure is axisymmetric, use 2D axisymmetric simulation to create a relatively small model to minimize computational requirements. Fig.5.15 shows the initial
geometry of the model. The bullet geometry shown represents the 3.78g lead bullet used in Setup I.

The high velocity spot impact welding model is comprised of four objects, including a deformable bullet (lead), two deformable sheets (6111-T4 aluminum) and a rigid die. The shape of the bullet has been changed slightly for simplicity but the mass has been maintained. The die was simulated as a rigid body in an effort to reduce the problem and shorten the analysis time and it remains fixed during the process. The bullet has an initial velocity of 250m/s. The right end of the sheets can only move in the x-direction. The analysis was done using dynamic coupled thermal displacement explicit simulation. 1833 axisymmetric, coupled displacement temperature, solid elements (4 node bilinear, reduced integration with hourglass control) were included in the model. The total CPU time is 3.42 seconds on an SGI origin 2000 workstation in Ohio supercomputer center.

The critical step in the simulation is the material definition and the contact algorithm. For modeling impact and heat related problems, material constitutive law should include rate and thermal effects. In the model, I choose Johnson-cook plasticity, which has the following yield stress expression:

\[
\tilde{\sigma} = \left[ A + B (\varepsilon_p^n) \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left( 1 - \hat{\theta}^m \right)
\]  

(5.1)

Where \( \varepsilon_p^n \) is the equivalent plastic strain and \( A, B, C, n \) and \( m \) are material parameters provided by the users, and \( \hat{\theta} \) is the non-dimensional temperature defined as:
\[
\hat{\theta} \equiv \begin{cases} 
0 & \text{for } \theta < \theta_{\text{transition}} \\
(\theta - \theta_{\text{transition}})/(\theta_{\text{melt}} - \theta_{\text{transition}}) & \text{for } \theta_{\text{transition}} \leq \theta \leq \theta_{\text{melt}} \\
1 & \text{for } \theta > \theta_{\text{melt}}
\end{cases}
\] (5.2)

where \(\theta\) is the current temperature, \(\theta_{\text{melt}}\) is the melting temperature, and \(\theta_{\text{transition}}\) is the transition temperature defined as the one at or below which there is no temperature dependence on the expression of the yield. The contact interaction between surfaces was the penalty algorithm. The friction behavior between contact surfaces was simplified as a constant in this model while different friction coefficients (0.2 and 0.8) were tried in the simulation process.

<table>
<thead>
<tr>
<th></th>
<th>A (Mpa)</th>
<th>B(Mpa)</th>
<th>C</th>
<th>n</th>
<th>m</th>
<th>Tm (k)</th>
<th>Transition (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (Johnson-cook plasticity)</td>
<td>265</td>
<td>426</td>
<td>0.015</td>
<td>0.34</td>
<td>1.0</td>
<td>925</td>
<td>298</td>
</tr>
<tr>
<td>Lead (linear hardening)</td>
<td>70</td>
<td>95.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>298</td>
</tr>
<tr>
<td>General properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young's modulus (Gpa)</td>
<td>70</td>
<td>0.279</td>
<td>2700</td>
<td>154</td>
<td>896</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>30</td>
<td>0.3</td>
<td>11350</td>
<td>32</td>
<td>132</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5 Material parameters used in the simulation
During the simulations, when the bullet geometry and mass were remained constant, the
die shape was changed to observe the different impact welding behavior of the two
sheets. The parameters chosen to change the die shape were pin radius, pin height and die
cavity radius. Meanwhile, When the bullet geometry and mass were changed to observe
the effect of bullet geometry on thinning effect and strain distribution, the die shape was
fixed.

5.6.2. Simulation Results

Comparison between experimental results and simulation results
As we can see from the experiments results, good bonding conditions were observed in
some cases. The excessive thinning of the upper sheet has major effect on the bonding
strength, and further causes the failure of the weld. Fig.5.16 is a simulation result with
original die and bullet shapes showing the strain distribution after impact welding. As
reported in the literature[6], the optimum deformation for the cold welding of aluminum
alloy sheets ranges from 50% to 90%. The simulation result in Figure 5.16 shows that the
equivalent strain around the rim area ranges from 0.75 to near 1.0, which promotes
bonding. In addition, the sharp corner of the pin was the major cause of the thinning.
Both results were consistent with the experimental results.
The numerical tool provides reasonable representation of the impact welding experiment, however, the thinning and non-consistent bonding remain big problems. Hence, reducing localized thinning was our first consideration to modify the die/pin geometry and to select different bullet shapes. As noticed both in modeling and experimental results, the sharp corner of the frustum shaped pin was the main cause for thinning. Therefore, step one was taken to change the pin shape to be like part of a sphere (domed shape). Fig.5.17 (a) shows reduced thinning when the pin was round. Additionally, the different die geometries and different bullet shapes were modeled as seen in Fig.5.17 from (a) to (c). The corresponding experimental results were shown in Fig.5.18 from (a) to (c). Both experiments and modeling results demonstrate that the hollow bullet with round tip (Fig.5.17 (a) and Fig.5.18 (a)) along with domed shaped pin gave us the best thinning distribution (The bullet cross-sections are shown in Fig.5.17 and the bullets are shown in Fig.5.18.

Energy calculation related to bonding metrics

The most challenging goal of the simulation is the identification of the bonding mechanism. From the temperature calculation in the simulation, it seems that the temperature increase was only 150K, which is significantly lower than the temperature ranges in explosive welding and friction welding, and closer to the temperature rise in ultrasonic welding. Roll bonding can be carried out at low temperature. Here sufficient shear strain or sheet extension can disrupt the oxide and cause clean metal to come into contact causing metallurgical bonding [1].
A useful metric has been developed in ultrasonic welding, which is, that if the friction work done per unit area exceeds a certain value the materials observed to join. This minimum energy criterion seems to be related to the applied normal force. For relatively small downward forces, increasing force decreases the energy required for bonding. This reaches a minimum. Beyond this minimum, the high frictional forces significantly inhibit the interface translation, which causes the required energy to increase [2,3,4]. We have calculated the frictional energy per unit area developed by relative sheet translation in the simulation as shown in Fig.5.19. We find that the energy per unit area is significantly less than that required for traditional ultrasonic welding. Whether this metric is appropriate or not is not clear for us.

*Simulation optimizing process parameters*

Although the impact spot welding has a very simple setup, the dynamic physics behind it is rather complex. Except for the bullet geometry influence in the impacting results, there are numerous other factors that will affect the final bonding possibility and quality. In this modeling, the interfaces that were in contact were only treated as Columb frictional interface for friction coefficient of 0.2 and 0.8. That will reflect the effect of surface finishes. As stated in the experimental section, the sheets with surface lubricant were difficult to bond.
As discussed in the previous section, the optimizing process was first targeted in reducing the thinning effect and comparing the bullet geometries. After that, additional optimization was concentrated on modifying the pin and die geometries. There are three parameters that were considered, the pin diameter and height and the die cavity diameter. The relative sliding of the contacting interface were plotted at locations 1 to 13 in fig. 5.19 for different pin diameters, pin heights and die cavity diameters. Fig 5.20 and 5.21 shows the effect of the pin diameter and height on the relative sliding between the contacting interfaces. The results indicate that both pin diameters and heights don not have significant effects on the bonding process. However, the effect of die cavity diameter as shown in Fig.5.22 has a large effect on the bonding process. As seen in Fig.5.22, when the die cavity increases from 8mm to 12mm, the highest sliding area which corresponding to high possibility for boding, shifts towards the die rim. This effect was also observed in the experiments.

5.7. Conclusions

We are developing a fundamentally new solid state welding procedure. It is based on a projectile with high kinetic energy forcing two sheets of metal into an appropriately contoured die. The method still requires significant development, but shows the following promising aspects:

- Bond strengths are comparable to spot welds.
- It offers the promise to join dissimilar metals.
• No heat-affected zone is formed.
• The equipment is light and versatile
• With optimization, this method may be a better choice than traditional spot welding in many circumstances.

Based on the simulation optimization, a series of new geometries were designed and tested in experiments. Results show that the following are the optimized process parameters:

• The hollow lead bullet with round tip gave the best bonding results for Al 6111-T4 1mm sheets. The mass of the bullet is 3.78-gram
• Stable bonding for Al 6111-T4 1mm thick sheets was achieved using the 3.78-gram lead bullet with impacting velocity range from 170m/s to 270m/s.
• 10mm and 12 mm die cavity diameter gave the best bonding results.
• Change the pin shape from truncated cone to domed shape reduced the thinning effect.
• The pin diameter and height used in the experiments were 4.5mm and 1.5mm.
References:


10. [www.osu.edu/hyperplasticity](http://www.osu.edu/hyperplasticity)


Figure 5.1 Schematic of Experimental Setup I
Figure 5.2  Cross-Sectional View of Hardened Steel Die/Pin
Figure 5.3  Test Setup II, based on a powder actuated tool
Figure 5.4  Pictures of experimental samples. (a) bonded samples; (b) obverse view of tab area; (c) reverse view of tab area.
Figure 5.5  Cross-section views of welded joints using a 3.78-gram lead projectile and setup I, 10mm diameter die with a 2.7mm pin depth.
Figure 5.6  An example showing tab diameter and inlet radius thinning
(3.78-gram projectile, 10mm die diameter with 2.7mm pin depth)
Figure 5.7  Cross-sectional view of target specimen showing uniform thinning (second generation die/pin setup)
Figure 5.8  The influence of impact energy on the bonding characteristic (a) low energy, no bond (b) moderate energy, good bond (c) high energy, tearing
Figure 5.9  Cross-sectional view of the best die/pin configuration: 12/B
Figure 5.10  Different projectile shapes and their characteristics
Figure 5.11 Hollowed out soft lead projectiles, 3.78 grams
Figure 5.12  Post impact projectile shape using setup II, 7.51 gram hollowed out
Figure 5.13  Post impact projectile shapes (a-f)
Figure 5.14  Obverse and reverse sides of magnesium specimens after shear testing
Figure 5.15  Initial geometry and mesh for the simulation
Figure 5.16 Effective plastic strain distribution in the sheets after impact welding
Figure 5.17  Effective plastic strain contour plot of the sheets for domed pin impacted by different bullet geometries

(a) Hollow bullet with round tip  (b) Bullet with hollow tip  (c) Solid bullet with round tip
Figure 5.18  Deformed sheets cross-section view upon impact from different bullet geometries. (a) Hollow bullet with round tip. (b) Bullet with hollow tip. (c) Solid bullet with round tip
Figure 5.19  Bonding energy of different locations (locations are those shown in the right)
Figure 5.20 Influence of pin diameter on the relative sliding at interface between upper and lower sheets
Figure 5.21  Influence of pin height on the relative sliding at interface between upper and lower sheets
Figure 5.22  Influence of die cavity diameter on the relative sliding at interface between upper and lower sheets
CHAPTER 6

6. ELECTROMAGNETIC IMPULSE WELDING

FEASIBILITY TEST OF DISSIMILAR MATERIALS

6.1. Introduction

Electromagnetic impulse welding is basically a solid state welding technique. It combines the advantages of solid state welding and high velocity forming. Recently this technology has been advanced to a point where it can be a viable, cost effective option for a variety of applications, especially for joining tubular components. During the magnetic pulse welding of two tubular components, the tubes are placed inside a coil (see Figure 6.1). The intense magnetic fields between the coil and flyer tube create high electromagnetic pressure between them. This magnetic pressure will drive the flyer tube to move towards the base tube and cause a strong impact between two metals. The impact pressure will sweep away the surface contaminants and force automatic bonding over the interface.
While traditionally difficult to join, tubular components are used in a variety of applications in an effort to reduce manufacturing costs, enhance strength and reduce weight. Such applications are primarily found in the automotive, aerospace and fluid industries. For example, in automotive industries, tubular hydroformed components has been utilized for a wide range of applications, from seat frames, side rails and engine cradles to steering columns, exhaust manifolds and camshafts. Electromagnetic impulse welding offers automotive engineers a cost effective and efficient means for joining hydroformed tubes. The aerospace industry also has potential to reduce overall manufacturing cost by utilizing magnetic pulse welding for producing tubular components, such as fuel lines.

Most researchers has found out that electromagnetic impulse welding has many similarities to explosive welding, such as the critical impact angle and velocity for joining and wavy interface after welding [1,2,3,4,5]. Additionally, the stand off distance between the flyer and base components was experimentally proven to be effective between one and three times flyer component thickness [1,2,3,4,5]. However, because electromagnetic impulse and explosive welding use different energy source to create impact, they have different characteristics and applications. In electromagnetic impulse welding, the magnetic pressure is hard to control due to the complexity of the electromagnetic fields. Therefore, the weld region is narrow (usually around 3mm). The primary applications for each technique are different. Magnetic impulse welding is typically used in joining tubular components, while explosive welding it primarily used for plate cladding.
In this chapter, two pairs of materials were studied using electromagnetic welding. They are aluminum 6061 to tungsten K1700 and Ti-3Al-2.5V to Inconel 625. First, explosive welding theory developed by Botros [6] and Cowan [7,8] was introduced to access the welding conditions (impact angle and velocity) of each material combination. Then finite element modeling was performed to determine the standoff distance between flyer and base tubes. At the same time, coil and concentrator dimensions were determined. Finally, electromagnetic welding experiments were conducted to study the weldability of each pair of materials.

6.2. Design considerations for high velocity impact welding

Figure 6.1 shows a schematic view of two typical electromagnetic setups. In the setup shown in Figure 6.1(a) (center joint), magnetic pressure drives the center of the flyer tube to impact the base tube first. The contact between the flyer and base tubes spreads in two directions, resulting in two welding regions. In the setup shown in Figure 6.1(b) (end-joint), the end of the flyer tube hits the base tube first, and the contact between them spreads only in one direction, resulting in one welding region. Typically, the end joint needs less capacitor energy to accelerate the flyer tube. As shown in Figure 6.1, the only difference between a center joint and an end joint is the relative position between coil and flyer tube, which is described by lap distance. Lap distance is defined as the amount of flyer tube length inserted into the coil, as shown in Figure 6.1.
The design of electromagnetic welding process involves three major steps. In step I the coil system was designed. Magneform INC provided the system, which consists of an aluminum coil and a Beryllium copper alloy concentrator (shown in Figure 6.2). The size of the aluminum coil is fixed, but the internal diameter of the concentrator can be changed based on different applications. In step II the welding criterion was chosen. This will be discussed in detail in the next paragraph. Finally, in step III coil-flyer and flyer-base gaps were determined by numerical modeling based on the chosen welding criterion. This design process by finite element simulation and will be discussed in section 6.3.

In this study, the design process will start from step II. Because of the welding interface similarity between electromagnetic impulse and explosive welding, explosive welding criterion was adapted to obtain weldability windows for different material combinations. The detail analysis and discussion can be found in reference [6,7,8,9].

Considering the oblique collision of two plates shown in Figure 6.3 [6]. Three controlling conditions were considered for weldability. These are: (1) the critical angle for jet formation, (2) the critical impact pressure for jet formation in the subsonic regime, and (3) the critical flow-transition velocity. For any impact state \((\beta, u_o)\), the impact pressure \(P\) can be described by:

\[
P = 1/2Z_{eq}u_o \cos \beta
\]  

(6.1)

Where \(Z_{eq}\) is the equivalent acoustic impedance of the colliding plates, defined by:
\[ Z_{eq} = \frac{2}{1/Z_1 + 1/Z_2} \]  \hspace{1cm} (6.2)

Where \( Z_1 \) is the flyer plate acoustic impedance \( (Z_1 = \rho_1 c_1) \), \( Z_2 \) is the base plate acoustic impedance \( (Z_2 = \rho_2 c_2) \), \( c_1 \) and \( c_2 \) are the speeds of sound in the flyer and target plate materials, respectively, and \( \rho_1, \rho_2 \) are the material densities, respectively.

The critical angle for jet formation in this study was defined as that angle at which either of the two flow velocities reaches the local speed of sound, (N.B. flow velocities denote \( U, V \) values as shown in Figure 6.3 in a frame of reference where the collision point \( C \) is frozen so that \( U = u_o/\tan \beta \) and \( V_c = u_o/\sin \beta \)). The critical angle \( (\beta_s) \) with respect to impact velocity \( u_o \) was named as Surge line. It can be defined from the following relations:

\[ \beta_s = \tan^{-1}(u_o/c_1), \text{ if } U = c_1, V_c < c_2 \]  \hspace{1cm} (6.3)

or

\[ \beta_s = \sin^{-1}(u_o/c_2), \text{ if } V_c = c_2, U < c_1 \]  \hspace{1cm} (6.4)

In the application of Al 6061-T4 to tungsten, the Surge line is shown in Fig.6.4. A characteristic feature of bonds obtained by impact welding is the wavy interface after welding. Welds transition from laminar-type interface to the wavy interface has been discussed by Cowan et al [7,8]. The Cowan expression for the laminar /wavy interface transition Reynolds number \( R_{T}^{(c)} \) is:

\[ R_{T}^{(c)} = (\rho_1 + \rho_2)V^2_{c,T}/2(H_{d1} + H_{d2}) \]  \hspace{1cm} (6.5)
Where $V_{c,T}$ is the transition value of the collision point velocity, $\rho$ is density, $H_d$ is static hardness, and subscripts 1,2 refer to the flyer and target plates, respectively. This expression has been widely used. It gives values of $R_{T}^{(c)}$ close to 10.6.

Since static hardness is a static material property, Wittman [9] has pointed that use of Hugnoit elastic limit (HEL) pressure instead of static hardness is fundamentally correct. Because HEL pressure is a dynamic property, it is more suited than hardness to impact phenomena. His expression, $R_{T}^{(w)} = (\rho_1+\rho_2)V_{c,T}^2/2(HEL_1+HEL_2)$, gives $R_{T}^{(w)} = 12.5 \pm 1.0$ for any combination of metals of known HEL values. In the present study, Wittman’s expression was used to calculate the flow transition lines (named as Cowan line) for Al 6061-T4 and Ti-3Al-2.5V as shown in Figure 6.4 and 6.13, respectively.

**6.3. Design methodology**

**6.3.1. Initial conditions for design:**

Two problems were modeled in the design process of this project. The first one is welding aluminum 6061-T4 tube to tungsten K1700 rod. In this case, the Tungsten rod is 0.435” in diameter, and the aluminum has wall thickness of 0.035” and will be machined to diameter decided by the design process. The second case is welding Ti-3Al-2.5V tube to Inconel 625 tube. The titanium tube is 0.875” in diameter with 0.035” wall thickness,
and the inconel 625 tube is 0.5” in diameter with 0.049” wall thickness. The inconel tube can be sized to fit the gap designed by the modeling.

6.3.2. Design case I: Al 6061-T4 tube to Tungsten K1700 rod

Table 6.1 summarizes the material properties for the design work in this project.

<table>
<thead>
<tr>
<th>Material mechanical behavior</th>
<th>Aluminum 6061-T4: Johnson-Cook plasticity [10]: ( Y = (A+B\varepsilon^n)(1+C\ln\varepsilon)(1-T^m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>110 Mpa</td>
</tr>
<tr>
<td>B</td>
<td>256 Mpa</td>
</tr>
<tr>
<td>n</td>
<td>0.34</td>
</tr>
<tr>
<td>C</td>
<td>0.015</td>
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<tr>
<td>m</td>
<td>1</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>General properties</th>
<th>K1700 Tungsten: Von Mises plasticity [13] ( S = 2G\varepsilon^D )</th>
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</thead>
<tbody>
<tr>
<td>Shear modulus G</td>
<td>120 Gpa</td>
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<tr>
<td>Yield strength</td>
<td>63.3 Mpa</td>
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<table>
<thead>
<tr>
<th>Material mechanical behavior</th>
<th>Aluminum 6061-T4 [12]</th>
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<tr>
<td>Density: 2700 Kg/m³</td>
<td>Specific heat: 896 J/Kg °C</td>
</tr>
<tr>
<td>Electric resistivity: 4.3e-8 ohm-m</td>
<td>Poisson’s ratio: 0.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>General properties</th>
<th>Tungsten K1700 [13]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density: 17090 Kg/m³</td>
<td>Electrical resistivity: 5.5e-5 ohm-m</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio: 0.28</td>
</tr>
</tbody>
</table>

Table 6.1  material properties for Al 6061-T4 and K1700 Tungsten
**Weld window of aluminum 6061-T4 to tungsten K1700**

The weld window was calculated based on the welding criterion described in section 6.2. As validated in explosive welding, for a weld to occur, the impact angle between the flyer and base plate must exceed the critical angle for jetting. This criterion reflected in the weld window was called surge line. Meanwhile, to achieve stable welding quality, the wavy welding interface after impact should be achieved to obtain the optimum welding strength. The transition condition for lamellar to wavy interface was named as Cowan line in the welding window. Figure 6.4 shows the constructed welding window for Al6061-T4 based on the above welding criterion.

**Modeling setup**

The modeling work was done using multi-physics code MPone. Since the entire setup is perfectly axisymmetric, 2D axisymmetric simulation was used to model the process and obtain the design parameters. Figure 6.5 shows the simulation setup. In this setup, the gap between the Al tube and coil was set to 0.06” based on the insulation thickness. The gap between the Al tube and tungsten rod was chosen as 0.07” (2*tube thickness). The rod and tube were modeled as axisymmetric solid elements. The coil was modeled as current carrying particles, which were treated as integration points in the calculation. EFG (Element Free Galerkin) method was used as the main solver for both mechanical and electromagnetic analysis. Except all the geometrical boundary conditions and material properties, current trace in the coil was estimated from bank system parameters and input
into the coil particles as initial condition for electromagnetic analysis. The bank system parameters are listed in table 6.2.

<table>
<thead>
<tr>
<th>Capacitance (Farads)</th>
<th>Inductance (Henrys)</th>
<th>Resistance (Ohms)</th>
<th>Full voltage (Kv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8e-3</td>
<td>3.148e-7</td>
<td>27.11e-3</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6.2 Bank system parameters

When calculating the input current, the unknown is the coil and concentrator inductance and resistance. These were estimated from previous experiments. Figure 6.6 shows the current trace that was input into the coil.

Welding condition analysis

After each running, output information was gathered for welding condition analysis. Three kinds of conditions are needed for the analysis. They are contour plot, tube nodal velocity, and tube nodal displacement at each time increment. The deformation contour plot for Al tube to tungsten rod was shown in Figure 6.7. As seen in the Figure, tube and rod impact occurs approximately at 5.4μs and welding occurs between 5.4μs and 7.2μs. Meanwhile, based on the displacement and velocity information of each tube node, the
impact velocity and angle between the tube and rod from 5.4µs to 7.2µs can be calculated as seen through Figure 6.8 to Figure 6.11.

For example, in figure 6.8, combining the velocity and angle profile, the impact point was determined at y=0.0148mm with impacting velocity of 630m/s and impacting angle of 16 degree. Same analysis was done for figure 6.9 through figure 6.11. The welding conditions were then plotted in the welding window as shown in Figure 6.12. The welding length was estimated as 3mm.

The weld points shown in Figure 6.12 indicate that our design for tube-coil and tube-rod gaps is successful. In the next experiments, the Al tube diameter was machined to 0.645”(rod diameter+2*tube-rod gap+tube thickness) based on the above design. The concentrator inner diameter was designed as 0.765” based on the calculated tube-coil gap. Lap distance can be adjusted during the experiments.

6.3.3. Design case II: Ti-3Al-2.5V tube to Inconel 625 tube

Table 6.3 summarizes the material properties for Ti-3Al-2.5V and Inconel 625 used in the modeling.
Material mechanical behavior

<table>
<thead>
<tr>
<th>Material</th>
<th>Ti-3Al-2.5V: Johnson-Cook plasticity [11]: ( Y = (A + Be^n) \left(1 + C \ln \varepsilon \right) \left(1 - T^m \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500 Mpa</td>
</tr>
<tr>
<td>B</td>
<td>1168 Mpa</td>
</tr>
<tr>
<td>C</td>
<td>0.027</td>
</tr>
<tr>
<td>Tm</td>
<td>1</td>
</tr>
<tr>
<td>Inconel 625: Von Mises plasticity [12]</td>
<td>( S = 2G E^D )</td>
</tr>
<tr>
<td>Shear modulus G</td>
<td>79.6Gpa</td>
</tr>
</tbody>
</table>

General properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Ti-3Al-2.5V</th>
<th>Inconel 625</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4480 Kg/m³</td>
<td>8440 Kg/m³</td>
</tr>
<tr>
<td>Specific heat</td>
<td>525 J/Kg °C</td>
<td></td>
</tr>
<tr>
<td>Electric resistivity</td>
<td>1.27e-6 ohm-m</td>
<td>1.25e-6 ohm-m</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 6.3  Material properties for Ti-3Al-2.5V and Inconel 625

Mechanical properties for Ti-3Al-2.5V were obtained through curve fitting the stress-strain curve in published paper [11]. Properties of Inconel 625 were obtained through metals handbook.

**Modeling design process**

The design process for Ti alloy to 625 Inconel is the same as the previous case except that a cooper driver was used in this case. The reason for using cooper driver is that the electric resistivity of Ti-3Al-2.5V is too high. When the tube electric resistivity is high, induced current in the tube will be very low. The magnetic pressure between the coil and tube is proportional to the induced current. Therefore, without the copper driver, even with full capacitor voltage, it is impossible to achieve the required velocity for the Ti
tube. Figure 6.13 is the weld window for Ti-3Al-2.5V to Inconel 625. Figure 6.14 is the axisymmetric modeling setup.

In figure 6.14, the tube-rod gap is 0.0875”(2.5*tube thickness), and the driver-coil gap is 0.06”. The copper driver has thickness of 0.0175” and height of 0.5” (based on available copper sheets). During the experiments, copper driver was added simply wrapping layers of copper sheets around the tube outer circumference. Since solid nuggets supported the inconel rod during experiments, the internal surface of the rod was fixed in the modeling. The input current for this modeling is the same as the previous case.

*Modeling results*

Figure 6.15 shows the deformation profile at different time increments. Impacting occurs at time 7.2μs, and welding occurs between 7.2μs and 9.6μs. However, only when the impacting velocity and angle were calculated at the above time increments, could the welding condition be extracted from combining information. Followed the same procedure as the Al-Tungsten case, figures 6.16 to 6.22 summarize the impacting velocity and angle at different times. Meanwhile, those conditions were plotted in the welding window as shown in figure 6.23. The welding condition was not as idea as in the Al-tungsten case. However, since there is some flexibility in the experiments, it is an acceptable design.
6.4. Experimental Results

6.4.1. Equipment and setup

Following the design process, Al 6061-T4 and Inconel tubes were machined to 0.645” and 0.63” in diameter, respectively. The concentrator designs are shown in figure 6.24 and 6.25. All concentrators are made of beryllium copper alloy for consideration of good conductivity and high strength.

The experiments were done on a 90 KJ capacitor bank system (Figure 6.26) in Edison Welding Institute, INC (EWI). The coil system is shown in Figure 6.2. The aluminum coil is directly connected with the capacitor bank using cables. The concentrator sits inside the aluminum coil. On the support table, there is a roller system connected with the clamp on each side of the concentrator. The clamps were used to support the flyer and base components. Therefore, the roller systems can control the positions of the tubes on two sides of the concentrator with respect to the concentrator.

6.4.2. Initial welding trials

According to the modeling results, there should be plenty of room to make a weld happen for Al 6061-T4 tube to tungsten K1700 rod. Therefore, the first set of experiments was done using 50% of bank energy and only the lap distance was adjusted. Figure 6.27 shows the result from first experimental trial.
However, as can be seen from Figure 6.27, one aspect was not considered in the modeling, the resistance heating of the tube. In (a) and (b), the excessive resistance heating fried end of the tubes and left no bond for tube to rod. For these two cases, the results indicate that the tube accelerated too fast and the impact occurred faster than the current rise time. In figure 6.27 (c), as the tube being inserted further into the coil, the deformation resistance increases and not much excessive energy left to fry the end of the tubes. Nevertheless, another problem was revealed in (c), which is that the low ductility of Al 6061-T4 caused cracks in the tube after welding.

6.4.3. Experimental adjustments and final results

In order to solve the problems in the first experimental trail, three major steps were taken before the next set of experiments. They are (1) heat treatment of the Al 6061-T4 tubes to increase its ductility (at 800°F for 20 minutes then air cool); (2) Wrap 0.03” copper driver around the Al tube to increase coupling efficiency and reduce resistance heating of the tube; (3) take metallurgical examination of the bonded area to adjust the energy level.

The second set of experiments was very successful. Figure 6.28 shows some of the bonded tubes. The tubes after bonding that have the best surface finish and strength combination were welded using 45% of full bank energy (40.5 KJ) and 1/4” past full land.
Some of the bonded tubes were cut and sectioned for metallurgical analysis. Figure 6.30 shows two typical results at 45% of full bank energy (40.5KJ). The welded samples have wavy interface similar as explosive welding.

As shown in figure 6.30, the welded sample using copper driver has more pronounced wavy interface than the same welding without copper driver, which indicates that the impact using copper driver occurred under bigger magnetic pressure. Copper driver increases the electromagnetic coupling efficiency and pressure for impact. Welded samples were also collected for tensile strength test and He leak test to evaluate the welding quality. Tensile test failures in the base tube where away from the weld region (figure 6.31). He leak test in most tubes were around 1e-10.

6.4.4. Experimental trials for Ti-3Al-3.5V to Inconel 625

Because of limited condition in machine time, only four samples were tried for Ti to Inconel. As can be seen from the design process, because of the high strength of the Ti tube, it is much harder to achieve good joints for this set of material combination. Therefore, for the four samples, only partially welding was obtained. Figure 6.32 shows a welded sample. Figure 6.33 shows the wavy interface after welding.
6.5. Discussions and Conclusions

The successful welding of aluminum to tungsten alloy and titanium alloy to inconel demonstrate the ability of electromagnetic impulse in joining dissimilar materials. As a high velocity impact welding technique, electromagnetic impulse welding has a lot similarity as explosive welding. However, because its unique mechanism and characteristics, it has great optional in joining tubular components in automotive, aerospace and fluid industries. The advantages of magnetic impulse welding can significantly reduce the manufacturing cost in many ways as summarized in table 6.4.
<table>
<thead>
<tr>
<th>High strength joints (stronger than parent material)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leak free welds</td>
</tr>
<tr>
<td>High welding speed (in the millisecond range)</td>
</tr>
<tr>
<td>Joining dissimilar materials and difficult-to-weld materials (303 stainless steel)</td>
</tr>
<tr>
<td>Cold processing (parts can be immediately handled)</td>
</tr>
<tr>
<td>No heat affected zone, minimal distortion</td>
</tr>
<tr>
<td>No post cleaning operations</td>
</tr>
<tr>
<td>No postweld heat treatment</td>
</tr>
<tr>
<td>No filler materials and no shielding gases</td>
</tr>
<tr>
<td>Easy for automation</td>
</tr>
<tr>
<td>Reduced environmental concerns</td>
</tr>
</tbody>
</table>

Table 6.4   Advantages of electromagnetic impulse welding
Although electromagnetic impulse welding is a flexible and easy to setup technology, the design process is still a challenge for engineers because of the complexity of electromagnetic interactions. The first challenge is coil design. In this study, the tubes being welded were under compression, which makes coil design relatively easier. For expansion welding, coil design still remains a big problem. In this study, basic design criterion adapted from explosive welding combining finite element modeling provides start points for different material combinations. However, as seen in both cases in this study, strictly following with modeling results cannot give good welds because some effects (such as heating) were not considered in the simulation. Fortunately, the process itself is flexible and a lot of factors are easy to adjust in the experiments. This makes the basic design feasible for our applications. Nevertheless, in the future, for more stable and precise welding design, more knowledge needs to be explored to allow engineers to apply this technology easily and confidently.
Reference:


12. www.matweb.com

13. Information provided by material manufacturer.
Figure 6.1 Schematic view of electromagnetic setups (a) center joint (b) end joint
Figure 6.2  Coil system
Figure 6.3  Oblique collision of two plates [6]
Figure 6.4  Welding window for Al6061-T4 to tungsten K1700
Figure 6.5 MPone modeling setup for Aluminum to Tungsten
Figure 6.6  Input current trace estimated based on previous experiments
Figure 6.7  Deformation profile at different time (a) 4.8µs  (b) 5.4µs  (c) 6.0µs  (d) 6.6µs  (e) 7.2µs
Figure 6.8  Impact velocity and angle plot for Al tube to tungsten rod at time 5.4\mu s
Figure 6.9  Impact velocity and angle plot for Al tube to tungsten rod at time 6.0µs
Figure 6.10  Impact velocity and angle plot for Al tube to tungsten rod at time 6.6µs
Figure 6.11  Impact velocity and angle plot for Al tube to tungsten rod at time 7.2μs
Figure 6.12  Weld points on the weld window for Al tube to Tungsten rod (tube-coil gap is 0.06”, tube-rod gap is 0.07”, lap distance is 0.3”)

![Graph showing weld points, cowan line, surge line, and weld points on a plot with angle in degrees on the x-axis and impact velocity in m/s on the y-axis.](image-url)
Figure 6.13  Weld window for Ti-3Al-2.5V to Inconel 625
Figure 6.14  Modeling setup for Ti-3Al-2.5V to Inconel 625
Figure 6.15  Deformation profile for Ti-3Al-2.5V impacting to Inconel 625 at different times (a) 7.2µs (b) 7.6µs (c) 8.0µs (d) 8.4µs (e) 8.8µs (f) 9.2µs (g) 9.6µs
Figure 6.16 Impacting velocity and angle plot for Ti-3Al-2.5V tube to Inconel 625 tube at time 7.2μs
Figure 6.17  Impacting velocity and angle plot for Ti-3Al-2.5V tube to Inconel 625 tube at time 7.6μs
Figure 6.18  Impacting velocity and angle plot for Ti-3Al-2.5V tube to Inconel 625 tube at time 8.0µs
Figure 6.19   Impacting velocity and angle plot for Ti-3Al-2.5V tube to Inconel 625 tube at time 8.4µs
Figure 6.20  Impacting velocity and angle plot for Ti-3Al-2.5V tube to Inconel 625 tube at time 8.8μs
Figure 6.21  Impacting velocity and angle plot for Ti-3Al-2.5V tube to Inconel 625 tube at time 9.2μs
Figure 6.22  Impacting velocity and angle plot for Ti-3Al-2.5V tube to Inconel 625 tube at time 9.6μs
Figure 6.23  Weld points on the weld window for Ti-3Al-2.5V tube to Inconel 625 tube

(Ti-Inconel gap is 0.875”, driver-coil gap is 0.06”)
Figure 6.24 Concentrator design for Al 6061-T4 tube to tungsten K1700 rod
Figure 6.25  Concentrator design for Ti-3Al-2.5V tube to Inconel 625 tube
Figure 6.26  90 KJ capacitor bank at EWI
Figure 6.27  First experimental trial for Al 6061-T4 to tungsten K1700 rod (a) full land, no weld (b) half land, no weld (c) 1/2” past full land, some bonding
Figure 6.28  Bonded tubes
Figure 6.29  Al-W interface after welding at magnification of x200 (a) 45% of full energy, without copper driver, small wavy interface (b) same energy with copper driver, heavy wavy interface
Figure 6.30  Tensile test breaks in the base tube (Al-W)
Figure 6.31  Welded sample for Ti-3Al-2.5V to Inconel 625 tubes
Figure 6.32  Wavy interface after welding for Ti-3Al-2.5V tube to Inconel 625 Tube
CHAPTER 7

7. Conclusions and Future Works

Through the process of this research, the main objective has been the development of three different joining technologies and the numerical modeling of these technologies to help design process parameters and understand joining mechanisms. Projectile spot impact welding is a new process developed in our group. The joining capability has been demonstrated by achieving strong joints similarly to spot welding between 1mm aluminum sheets. The influence of different process parameters, such as projectile type and velocity, die and pin geometry and surface conditions, has been investigated both experimentally and numerically. Electromagnetic crimping is a mechanical joining process. This technology has already been used in the industries. However, very little data is available for the design and performance of this type of joint. In this research, the joint strength was proved to be around 80% of the parent material for joining aluminum tube to the nuts. In addition, the electromagnetic crimping for 0.5” aluminum rings to different mandrel materials has been studied through both experiments and numerical modeling. Through strain measurement, the residual hoop stress in the ring was shown to be near
the yield strength of the ring materials. Mandrel with higher compliance provided higher interference strains. Electromagnetic impact welding is a solid-state welding technique similar to explosive welding. During this research, process parameter relationships established in explosive welding were adapted and combined with numerical modeling to provide a design methodology for electromagnetic impact welding. The capability of electromagnetic impact welding to join dissimilar materials has been demonstrated through the welding of two different material combinations, aluminum 6061 to tungsten K1700 and Ti-3Al-2.5V to Inconel 625. Slightly wavy bond interfaces were observed for both material combinations.

Although the advantages of high velocity joining techniques make them attractive technologies in the current industrial environment, the design and numerical modeling of these processes are still very difficult. High velocity impact deformation involves wave propagation in the materials. As detailed in chapter 2, some codes (ABAQUS and AUTODYN) can deal with wave propagation correctly. In addition, when dealing with impact deformation, material properties are complex under high pressure and high strain rate, especially at the impact interfaces. This is probably the critical reason for the failure of predicting the residual hoop stress in the ring-crimping problem by commercial codes. Meanwhile, when solving the physics of high velocity techniques, for example, electromagnetic deformation, the process becomes even more complex. During the electromagnetic deformation, the interaction of electromagnetic fields is complex and the modeling software is still under development as discussed in previous chapters, and no
codes are easy to use and reliable in this realm. Therefore, in this research, the numerical modeling of different joining techniques should be considered a preliminary study. In the future, more research and code development may provide better and more robust design process of these technologies.

When comparing the characteristics of the three joining technologies investigated in this research, both spot impact welding and electromagnetic impact welding fall inside the family of solid state welding, while electromagnetic crimping is a mechanical joining process. All three joining processes are very fast, in the range of tens of microseconds. However, the interface temperatures during these welding processes are different. Electromagnetic impact welding has the highest interface temperatures among the three, while electromagnetic crimping has the lowest interface temperature. These can also be compared with some traditional joining techniques. For example, fusion and spot welding involve the melting of materials during the welding process, and they are also much slower than high velocity joining techniques. Figure 7.1 shows plot of several joining techniques regarding the joining time and interface temperatures. Both fusion and spot welding are fusion welds mechanism, explosive welding, electromagnetic impact welding and spot impact welding are all solid state welding processes, and electromagnetic crimping and double seaming are mechanical joining mechanism.

The three joining technologies in this research are all in some sense new processes. In order to fully utilize them in automotive and aerospace applications, more process
development tools are needed in the future. For examples, numerical analysis helped immensely through the design and understanding of these processes in this research. However, there are still some software limitations. Therefore, dynamic simulation of the high velocity impact deformation needs to be improved in the future to better capture the factors influencing the processes. Two directions are important, interface energy conversion during high-pressure collision and large deformation with complex wave propagation. In addition, the modeling capability of electromagnetic fields interaction is essential for the progress of electromagnetic joining techniques. This is a big obstacle for achieving stable designs for joints and forming processes. This can be solved in two directions. The first is integrating existing electromagnetic analysis codes with mechanical analysis codes. This can be done in either loose coupling or full coupling. The second is developing fully coupled electromagnetic-mechanical analysis code such as MPone. This is a longer and more difficult task. With the full capability of dynamic mechanical simulation and electromagnetic analysis, the design process of the three techniques can be dramatically improved. More importantly, they can fit into the production market in a short amount of time.
Figure 7.1  A bonding map for different joining processes

EW – Explosive Welding
EMW – Electromagnetic Impact Welding
SIW – Spot Impact Welding
EMC – Electromagnetic Crimping
SW – Spot Welding
FW – Fusion Welding
DS – Double Seaming
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